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Benzene Fugitive Emissions
Background Information for Proposed Standards

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Benzene Fugitive Emissions — Background Information for Proposed Standards

Emission Standards and Engineering Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

November 1980

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PUBLICATION NO. EPA-450/3-80-032a

ENVIRONMENTAL PROTECTION AGENCY

Background Information and Draft Environmental Impact Statement for Benzene Fugitive Emissions

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1. The proposed national emission standard would limit fugitive emissions of benzene from existing and new petroleum refining and chemical manufacturing units. The proposed standard implements Section 112 of the Clean Air Act and is based on the Administrator's determination of June 8, 1977, (42 FR 29332) that benzene presents a significant risk to human health as a result of air emissions from one or more stationary source categories, and is therefore a hazardous air pollutant.

2. Copies of this document have been sent to the following: Federal Departments of Labor, Health and Human Services, Defense, Transportation, Agriculture, Commerce, Interior, and Energy; the National Science Foundation; and Council on Environmental Quality; members of the State and Territorial Air Pollution Program Administrators; the Association of Local Air Pollution Control Officials; EPA Regional Administrators; and to other interested parties.

3. The comment period for review of this document is 75 days and is expected to begin on or about December 15, 1980.

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METRIC CONVERSION TABLE

EPA policy is to express all measurements in agency documents in metric units. Listed below are metric units used in this report with conversion factors to obtain equivalent English units. A list of prefixes to metric units is also presented.

To Convert Metric Unit	Multiply By Conversion Factor	To Obtain English Unit
centimeter (cm)	0.39	inch (in.)
meter (m)	3.28	feet (ft.)
liter (l)	0.26	U.S. gallon (gal)
cubic meter (m^3)	264.2	U.S. gallon (gal)
cubic meter (m^3)	6.29	barrel (oil) (bbl)
kilogram (kg)	2.2	pound (lb)
megagram (Mg)	1.1	ton
gigagram (Gg)	2.2	million pounds (10^6 lbs)
gigagram (Gg)	1102	ton
joule (J)	9.48×10^{-4}	British thermal unit (Btu)
gigajoule (GJ)	9.48×10^5	British thermal unit (Btu)
Degree Celsius (°C)	(°C x 1.8) + 32	Degree Fahrenheit (°F)
Cubic meters/second (m^3/sec)	4.40	gallons/minute (gal/min)

PREFIXES

Prefix	Symbol	Multiplication Factor
tera	T	10^{12}
giga	G	10^9
mega	M	10^6
kilo	k	10^3
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}

1.0 SUMMARY

1.1 STATUTORY AUTHORITY

National emission standards for hazardous air pollutants are established in accordance with Section 112(b)(1)(B) of the Clean Air Act (42 U.S.C. 7412), as amended. Emission standards under Section 112 apply to new and existing sources of a substance that has been listed as a hazardous air pollutant. This study examines fugitive emission sources in benzene service (containing 10 or more percent by weight benzene) in petroleum refining and organic chemical manufacturing industries.

1.2 REGULATORY ALTERNATIVES

Six regulatory alternatives were developed by employing various combinations of the available control techniques in the affected industry. Reflecting increasing levels of emission reduction, these alternatives range from requiring no new controls to eliminating all benzene fugitive emissions.

Regulatory Alternative I represents a baseline emission level that describes the industry in the absence of regulations for the control of benzene fugitive emissions. This alternative provides the basis for incremental comparison of the other regulatory alternatives.

Regulatory Alternative II would reflect emission controls equivalent to the recommendations suggested by the Control Techniques Guideline (CTG) document for refinery volatile organic compound emissions. Periodic leak detection and repair would be required for most sources as well as the installation of specified equipment for other sources. This alternative would result in a 57 percent reduction in benzene fugitive emissions from the baseline level.

Pumps and valves in liquid service would be monitored annually for leaks. Safety/relief valves, pipeline valves, open-ended valves, and compressors in gas service would be monitored for leaks on a quarterly basis. Open-ended valves would be sealed with a cap, blind, plug, or a second valve.

Regulatory Alternative III would result in a 73 percent reduction in emissions by increasing the frequency of leak detection and repair and by requiring additional equipment. Monthly leak detection and repair would be required for pumps, valves, and compressors. Open-ended valves would be sealed with a cap, blind, plug, or a second valve. Rupture disks would be installed on safety/relief valves, or as an alternative, they would be vented to a flare.

Regulatory Alternative IV would increase control efficiency to 77 percent by requiring additional specified equipment. In addition to the leak detection and repair and equipment requirements of Alternative III, Regulatory Alternative IV would require the use of mechanical seal systems on pumps and compressors in benzene service. In addition, degassing vents on pump seal oil reservoirs would be required to be vented to a closed system.

Regulatory Alternative V would effect a 90 percent control efficiency by requiring the installation of mechanical seals on pumps and compressors, the installation of diaphragm or sealed bellows valves on valves, and the sealing of open-ended valves. Closed-purge sampling systems would be installed and rupture disks would be installed on safety/relief valves.

Regulatory Alternative VI would result in a 100 percent control efficiency for benzene fugitive emissions by prohibiting all production and use of benzene in the affected industry.

1.3 ENVIRONMENTAL IMPACT

Included in the evaluation of environmental impacts were estimates of air quality, water, noise, and solid waste impacts. Table 1-1 summarizes the environmental impact assessments for each regulatory alternative.

Table 1-1. ENVIRONMENTAL AND ECONOMIC IMPACTS OF REGULATORY ALTERNATIVES

Alternative	Air Impact	Water Impact	Solid Waste Impact	Energy Impact	Noise Impact	Economic Impact
I (no action)	0	0	0	0	0	0
II	+2**	+1**	0	+1**	0	+1**
III	+2**	+1**	0	+1**	0	0
IV	+3**	+1**	0	+1**	0	-1**
V	+3**	+1**	0	+1**	0	-2**
VI	+4**	+1**	0	-2**	0	-4**

Key:

+ Beneficial Impact
- Adverse Impact

0 No impact
1 Negligible Impact
2 Small Impact
3 Moderate Impact
4 Large Impact

* Short-Term Impact
** Long-Term Impact
*** Irreversible

1.3.1 Air Quality Impact

1.3.1.1 Existing sources. For the existing industry including about 240 production units, total nationwide benzene fugitive emissions are estimated to be 8,300 megagrams per year (Mg/Yr) for the baseline alternative. Regulatory Alternative II would reduce these emissions 57 percent, from 8,300 Mg/Yr to 3,600 Mg/Yr. Alternative III would reduce emissions to 2,200 Mg/yr, yielding a 73 percent reduction. Alternative IV would yield a 77 percent reduction in benzene fugitive emissions to a level of 1,900 Mg/yr. Alternative V would reduce emissions to 900 Mg/yr, yielding a 90 percent reduction in emissions from the baseline.

1.3.1.2 New sources. For new sources through 1985 including 68 production units, total nationwide benzene fugitive emissions are estimated to be about 2,500 Mg/yr for Regulatory Alternative I (baseline). Regulatory Alternative II would reduce these emissions to about 1,100 Mg/yr, a 56 percent reduction through 1985. Alternative III would reduce emissions from about 2,500 Mg/yr to about 700 Mg/yr, a 72 percent reduction through 1985. Alternative IV would reduce emissions to about 500 Mg/yr, resulting in an 80 percent reduction through 1985. Alternative V would reduce emissions to about 200 Mg/yr, yielding a 92 percent reduction from the baseline alternative through 1985.

1.3.2 Water, Solid Waste, and Energy Impacts for New and Existing Sources

Since none of these alternatives would require any additional water discharges, there would be no negative impact on water quality. There is potential for a positive benefit to water quality, however, due to decreased amounts of organic materials entering drains, sewers, and waste water discharges because of better leak control. This benefit would increase with the stringency of the alternative because each successive alternative requires additional leak control measures.

There would be no significant solid waste or noise impact as a result of implementing any of the regulatory alternatives. Additionally, since the controls required to implement the alternatives are passive in nature, there would be no significant negative energy impact. In fact, there would be a slight energy benefit from the conservation of raw materials and products that results from the control of leaks.

1.4 ECONOMIC IMPACT

Industry total capital and annualized costs, including recovery credits, were estimated for Regulatory Alternatives II, III, IV, and V. These estimates for new and existing sources are based on second quarter 1979 dollars. Table 1-1 summarizes the economic impacts that result from these costs for each of the regulatory alternatives.

1.4.1 Existing Sources

Regulatory Alternative II would require a total capital investment of $2.9 million and would result in an annualized savings of $25 thousand. Alternative III would require a capital investment of $9.7 million and an annualized cost of $2.1 million. Alternative IV would require a capital investment of $25.3 million and an annualized cost of $5.5 million. Alternative V would require a capital investment of $242 million and an annualized cost of $58.6 million. It should be noted that these costs are for the entire industry and apply to 241 production units.

The annualized costs required to implement Alternatives II, III, IV, and V could cause the average prices of benzene derivatives to rise by 0.04, 0.13, 0.37, and 4.1 percent, respectively, if full pass-through of the costs is assumed.

1.4.2 New Sources

The costs of implementing the alternatives are lower for new sources than for existing ones because no retrofitting expenses are involved. Regulatory Alternative II would require a fifth-year capital investment of $820 thousand and would result in an annualized savings of $70 thousand in the fifth year after implementing this alternative. Alternative III would require a fifth-year capital investment of $2.2 million and an annualized cost of $420 thousand after five years. Alternative IV would require a fifth-year capital investment of $6.5 million and an annualized cost of $1.3 million after five years. Alternative V would require a capital investment of $48.4 million and an annualized cost of $11.4 million after five years. These cost estimates apply to 68 new production units built in the fifth year after implementing each alternative.

The annualized costs of implementing Regulatory Alternatives II through V for new sources (assuming full cost pass-through) could cause the average price of benzene derivatives to rise from 0.03 percent for Alternative II to 3.3 percent for Alternative V.

2. INTRODUCTION

2.1 BACKGROUND

The Environmental Protection Agency proposed on October 10, 1979, "Policies and Procedures for Identifying, Assessing, and Regulating Airborne Substances Posing a Risk of Cancer" (44 FR 58642). All standards for carcinogens regulated under Section 112 of the Clean Air Act are being developed in accordance with those proposed Policies and Procedures. The following is a Section quoted from the Policies and Procedures which describes the procedures for establishing standards once the decision has been made as to which pollutants are to be regulated.

> (2) The Proposed EPA Approach (44 FR 58642)
>
> The standard-setting policy proposed today requires, as a minimum, the use of "Best Available Technology" (BAT) to control emissions from source categories presenting significant risks to public health. The policy would also require additional controls, as necessary, to eliminate "unreasonable residual risks" remaining after the use of BAT. This approach is a judgmental one, designed to protect the public health with an ample margin of safety from risks associated with exposure to airborne carcinogens. The implementing procedure described below puts prime emphasis on public health, consistent with Section 112, but permits consideration of economic impacts and benefits of the activity in setting standards for each source category. Uncertainties in the assessments of risks, costs, and potential benefits, as well as the distributional (equity) problems of various situations, would also be considered in setting standards.
>
> (a) Source Categories Regulated
>
> The first step in establishing standards and requirements for pollutants listed under Section 112 under this proposed policy is the determination of which categories of sources emitting the pollutants will be regulated, and in what order

regulations will be developed. Although a pollutant may have been listed because emissions from a particular source category pose a significant risk, other source categories may also emit the pollutant in lesser amounts. This may occur, for example, because the sources process very little of the substance, because the substance is present in only trace amounts in the sources' raw materials, or because sources have installed adequate controls on their own initiative or in response to other regulatory requirements.

The Administrator will therefore propose regulations only for those source categories which may pose significant risks to public health. The determination of whether a source category emitting a listed pollutant poses a significant risk will be made on essentially the same basis as the listing decision, except that the more detailed exposure analysis and risk assessment then available will be used in lieu of the preliminary information used in the listing decision. As in the listing decision, the risk assessment will be used to indicate the existence of a significant risk where the exposure analysis alone is insufficient, but will not be used as evidence that a significant risk does not exist where the exposure analysis indicates to the contrary.

(b) Priorities for the Development of Standards

EPA anticipates that a substantial number of substances will be listed as carcinogenic air pollutants under Section 112 in the near future. It is also likely that many of these substances will be emitted in significant quantities from more than one source category. As a result, EPA will need to develop emission standards and other requirements for a large number of source categories emitting these substances. At least until generic standards can be developed for large groups of these sources, the resources that would be necessary to complete this task immediately far exceed those available to EPA for this purpose. Today's proposal therefore provides for the assignment of priorities to significant source categories for the development of these regulations, through publicly stated criteria and announced decisions.

Under today's proposal, source categories posing significant risks will be assigned priority status (high, medium, or low) for further regulatory action (beyond generic standards) on the basis of: (1) magnitude of projected total excess cancer incidence associated with current and future source emissions; (2) magnitude of cancer risks for the most exposed individuals; (3) ease of expeditious standards development and implementation; and (4) feasibility of significant improvements in controls. In addition, significant sources of more than one carcinogen may be given priority over single-pollutant sources, based on the sum of risks from the emitted substances.

A high priority will be assigned, for example, to a source category constituting an important problem requiring immediate attention, or where risks are somewhat lower but an appropriate regulatory solution is both feasible and readily available. Source categories assigned medium priority will generally be those that present lower risks and will be scheduled for standard development as resources become available. Lower risk source categories for which the extent of feasible control may be substantially limited will be assigned low priority for regulation development. Assignment to the low priority category will generally mean that active development of the regulations will not begin until there is some change in the factors which led to the assignment, or until higher priority actions have been completed.

(c) Regulatory Options Analysis

EPA will perform detailed analyses to identify alternative, technologically feasible control options and the economic, energy, and environmental impacts that would result from their application. Where substitution is determined to be a feasible option, the benefits of continued use of the substance or process will be considered. These analyses will rely primarily on the procedures and techniques employed by EPA for developing New Source Performance Standards under Section 111 of the Act.

The identification of feasible control options will initially survey the existing control devices at the sources within a particular category to determine the best controls currently in use. The potential emission points of the listed pollutant at a particular kind of facility will also be identified, as will possible emissions of carcinogens other than the specific one under study. EPA will, in addition, examine the applicability of available technologies which are not currently used by the industry to control the pollutant of concern (technology transfer) but which have been demonstrated in pilot tests or other industrial applications. Finally, the availability and adequacy of substitutes which would eliminate some or all emissions of the pollutant will be assessed.

Once the technologically feasible control alternatives, which may range from no further control to a complete ban on emissions, have been identified, the environmental, economic and energy impacts of these options will be determined. Considerations in these impact assessments will include for each option: the number of plant closures predicted and the direct impact on employment and end product prices; the impact on growth and expansion of the industry; the resulting changes in profitability; capital availability for control equipment; the impacts from the availability of substitute products and foreign imports; the potential increases in national energy consumption; and the impacts on other environmental media including increased water pollution and solid waste disposal. On the basis of these assessments, one of the control options identified will be designated as the BAT for the control of emissions from the sources in the category. This level of control will be that technology, which in the judgment of the Administrator, is the most advanced level of control adequately demonstrated, considering economic, energy, and environmental impacts.

The control level designated "best available technology" may be different for new and existing facilities in a category. For practical purposes, this level of control for new sources will, as a minimum, be equivalent to that which would be selected as the basis for a New Source Performance Standard (NSPS) under Section III. The requirement of "best available control technology" for new sources would consider "economic feasibility" and would not preclude new construction.

The selection of BAT for existing sources may require consideration of the technological problems associated with retrofit and related differences in the economic, energy, and environmental impacts. In practice, BAT for existing sources would consider economic feasibility and would not exceed the most advanced level of technology that at least most members of an industry could afford without plant closures.

(d) Minimum Requirements for Existing Sources

Final Section 112 standards will require existing sources in any regulated source category, as a minimum, to limit their emissions to the levels corresponding to the use of "best available technology." This requirement is based on the Administrator's judgment that any risks that could be avoided through the use of these feasible control measures are unreasonable. Whether BAT controls are sufficient to protect public health will be determined by a subsequent evaluation of the remaining risks.

(e) Determination of Unreasonable Residual Risk For Existing Sources

Following the identification of BAT for existing sources, the quantitative risk assessment described earlier will be used to determine the risks remaining after the application of BAT to the source category. If the residual risks are not judged by the Administrator to be unreasonable, further controls would not be required. If, however, there is a finding of unreasonable residual risk, a more stringent alternative would be required. Among the possible alternatives would be the immediate application of more restrictive emission standards, including those based on more extensive use of substitutes, and scheduled or phased reductions in permissible emissions. The alternative selected would be that necessary, in the Administrator's judgment, to eliminate the unreasonable residual risks.

Given the differences in the degree of certainty in risk estimates, in the numbers of people exposed, in benefits, in the distribution of risks and benefits, in the cost of controls, in the availability of substitutes, and in other relevant factors, it is not possible to state any precise formula for determining unreasonable residual risk. The determination will necessarily be a matter of judgment for each category involved. Nevertheless, the process followed and the various factors involved can be outlined.

The determination of unreasonable residual risk will be based primarily on public health, and will require protection with an ample margin of safety. To the extent possible, quantitative or qualitative estimates of various factors will be made for purposes of comparison. Among these are: (1) the range of total expected cancer incidence and other health effects in the existing and future exposed populations through the anticipated operating life of existing sources; (2) the range of health risks to the most exposed individuals; (3) readily identifiable benefits of the substance or activity; (4) the economic impacts of requiring additional control measures; (5) the distribution of the benefits of the activity versus the risks it causes; and (6) other possible health and environmental effects resulting from the increased use of substitutes.

3.0 SOURCES OF BENZENE FUGITIVE EMISSIONS IN PETROLEUM REFINING AND ORGANIC CHEMICAL OPERATIONS

3.1 INTRODUCTION

Valves, pumps, flanges, and other pieces of equipment are used extensively in the refining and organic chemical industries to move streams of organic compounds to and from various process vessels. Since this type of equipment can develop leaks, each individual piece is a potential source of organic compound emissions whenever it handles a process stream containing such compounds. When a piece of equipment handles a process stream containing benzene, it is a potential source of benzene emissions.

This chapter will discuss the types of equipment that can be sources of benzene fugitive emissions. Estimates of uncontrolled emission factors will also be presented, and the parameters which may influence the emissions will be discussed.

3.2 SOURCES OF BENZENE EMISSIONS

Benzene fugitive emission sources are pieces of equipment handling streams that could potentially contain benzene. These include sources that develop leaks after some period of operation due to seal failure as well as other sources that can emit benzene when used in specific conditions in the production unit. The sources that develop leaks due to seal failure are those using a sealing mechanism to limit the escape of organic compounds to atmosphere. These include pumps, pipeline valves, safety/relief valves, flanges, agitators, and compressors.

Other types of equipment are potential benzene fugitive emission sources for reasons other than leaking seals. These types of equipment might have the potential for benzene emissions, for example, because they vent organic materials that contain benzene to atmosphere. These types include process drains, sampling connections, open-ended valves, wastewater separators, cooling towers, product accumulator vessels, safety/relief valves, and process unit turnarounds.

3.2.1 Potential Leak Sources

3.2.1.1 Pumps. Pumps are used extensively in the refining and organic chemical industries for the movement of organic fluids. Centrifugal pumps are used most often in these industries, although positive-displacement pumps, reciprocating and rotary action pumps, and the specialized canned, diaphragm pumps, and magnetically coupled pumps are used for some applications. Except for the canned, diaphragm, and magnetically coupled types, the pumps have a shaft that requires a seal to isolate the pump's interior fluid from atmosphere. Packed and mechanical shaft seals are most commonly used. Proper installation and maintenance are required for all seal types if they are to function properly and retain their ability to seal. The possibility of a leak through this seal makes the pump a potential source of benzene emissions.

3.2.1.1.1 Packed seal. Figure 3-1 is a diagram of a simple packed seal. Packed seals can be used on both reciprocating and rotary action pumps. This seal consists of a stuffing box in the pump casing filled with specialized packing material that is compressed with a packing gland to fit closely around the shaft. To prevent buildup of frictional heat, lubrication is required. A sufficient amount of either the liquid being pumped or another liquid that is injected must be allowed to flow between the packing and the shaft to provide the necessary lubrication. Degradation of this packing and/or the shaft seal face after a period of usage can be expected to eventually result in leakage of organic compounds to atmosphere.

3.2.1.1.2 Mechanical seal. Figure 3-2 is a diagram of a basic single mechanical seal. The rotating seal-ring face and the stationary element face are lapped to a very high degree of flatness to maintain contact throughout their entire mutual surface area. As with packing, the faces must be lubricated; however, because of the seal's construction, much less lubrication is needed. There are many variations to the basic design, but all have the lapped seal face between a stationary element and a rotating seal ring. Again, if the seal becomes imperfect due to wear, the organic compounds being pumped can leak between the seal faces and can be emitted to atmosphere.

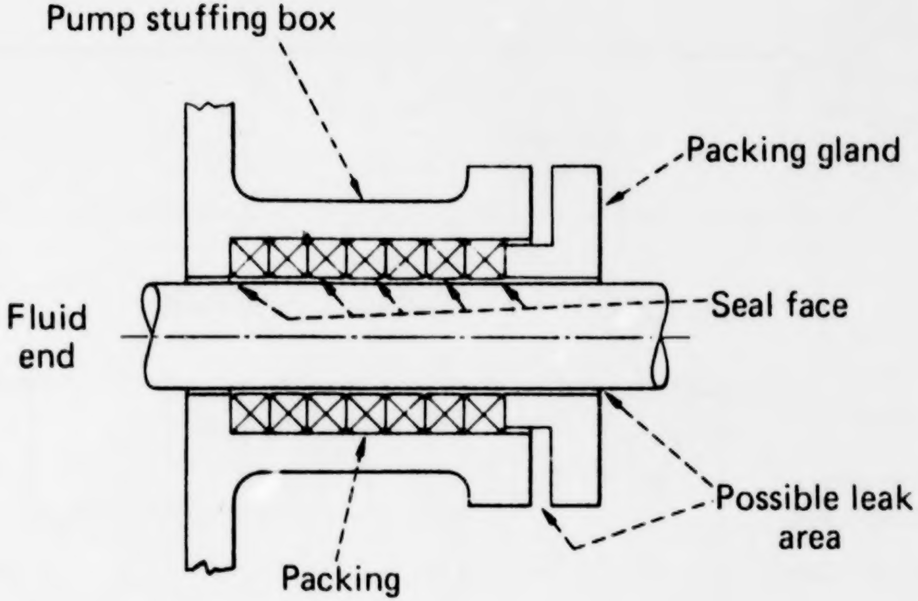
Pump stuffing box
Packing gland
Fluid end
Seal face
Possible leak area
Packing

Figure 3-1. Simple Packed Seal[1]

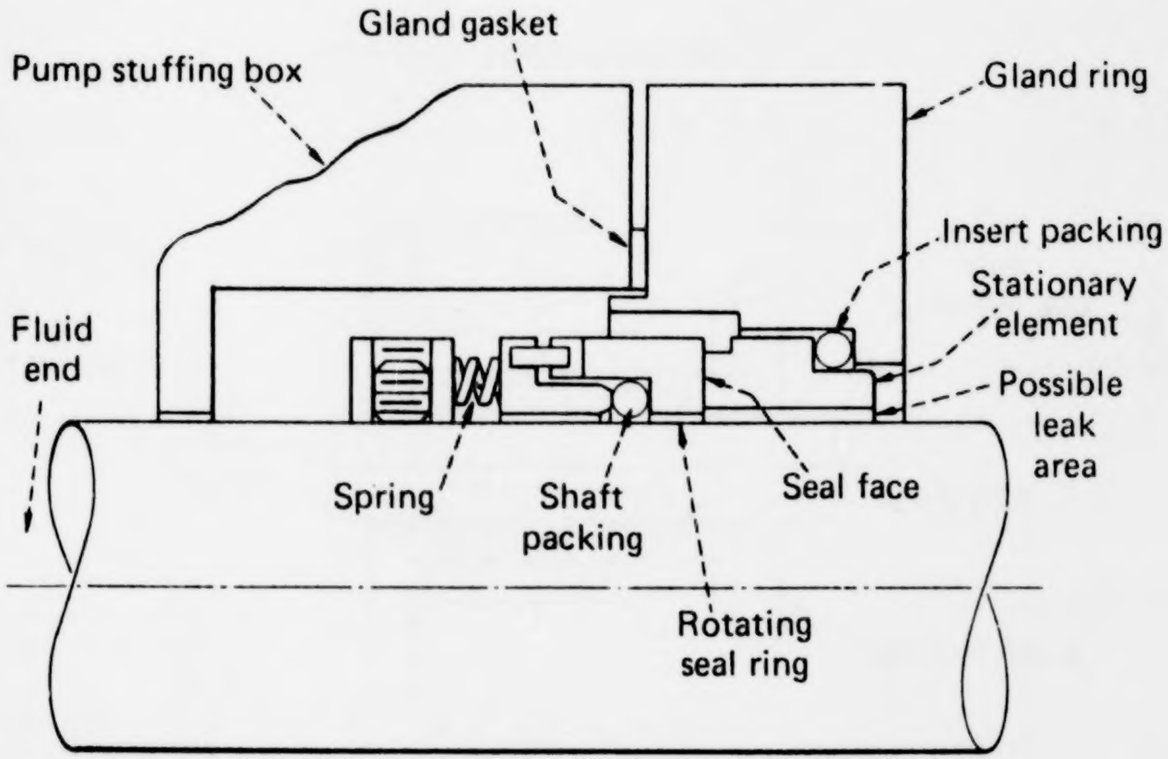
Gland gasket
Pump stuffing box
Gland ring
Insert packing
Stationary element
Fluid end
Possible leak area
Spring
Shaft packing
Seal face
Rotating seal ring

Figure 3-2. Basic Single Mechanical Seal[1]

3.2.1.2 Pipeline Valves. One of the most common pieces of equipment in a refinery or an organic chemical production unit is the valve. The types of valves commonly used are globe, gate, plug, ball, relief, and check valves. All except the safety/relief valve and check valve are activated by a valve stem, whose motion may be rotational or linear or both, depending on the specific design. This stem requires a seal to isolate the valve interior fluid from atmosphere. The possibility of a leak through this seal makes the valve a potential source of benzene emissions.

The most common type of valve stem seal in use is the packed seal. It consists of a stuffing box in the valve housing filled with specialized packing material that is compressed with a packing gland to fit closely around the stem. Figure 3-3 is a diagram of a globe valve with a packed seal.

3.2.1.3 Safety/Relief Valves. Safety/relief valves are required by engineering codes for applications where the pressure on a vessel or a system may exceed the maximum allowed. A spring-loaded safety/relief valve, which is shown in Figure 3-4, is typically used for this service. The seal is a flat disk held in place on a seat by a spring during normal system operation. The possibility of a leak through this seal makes it a potential source of benzene emissions. The potential causes for leaks are "simmering," a condition caused by the system pressure being close to the valve set pressure, improper reseating following a relieving operation, and corrosion or degradation of the valve seat.

3.2.1.4 Flanges. Flanges are bolted, gasket-sealed junctions used in joining pipe or equipment components, such as vessels, pumps, valves, and heat exchangers, that may require isolation or removal. The possibility of a leak through the gasket seal makes flanges potential sources of benzene emissions.

Two primary causes of leakage are seal deformation, due to thermal stress on the adjoining piping or equipment, and opening of the flange without replacement of the gasket.

3.2.1.5 Compressors. Compressors, like pumps, can be both centrifugal and positive displacement types. Compressors have a shaft

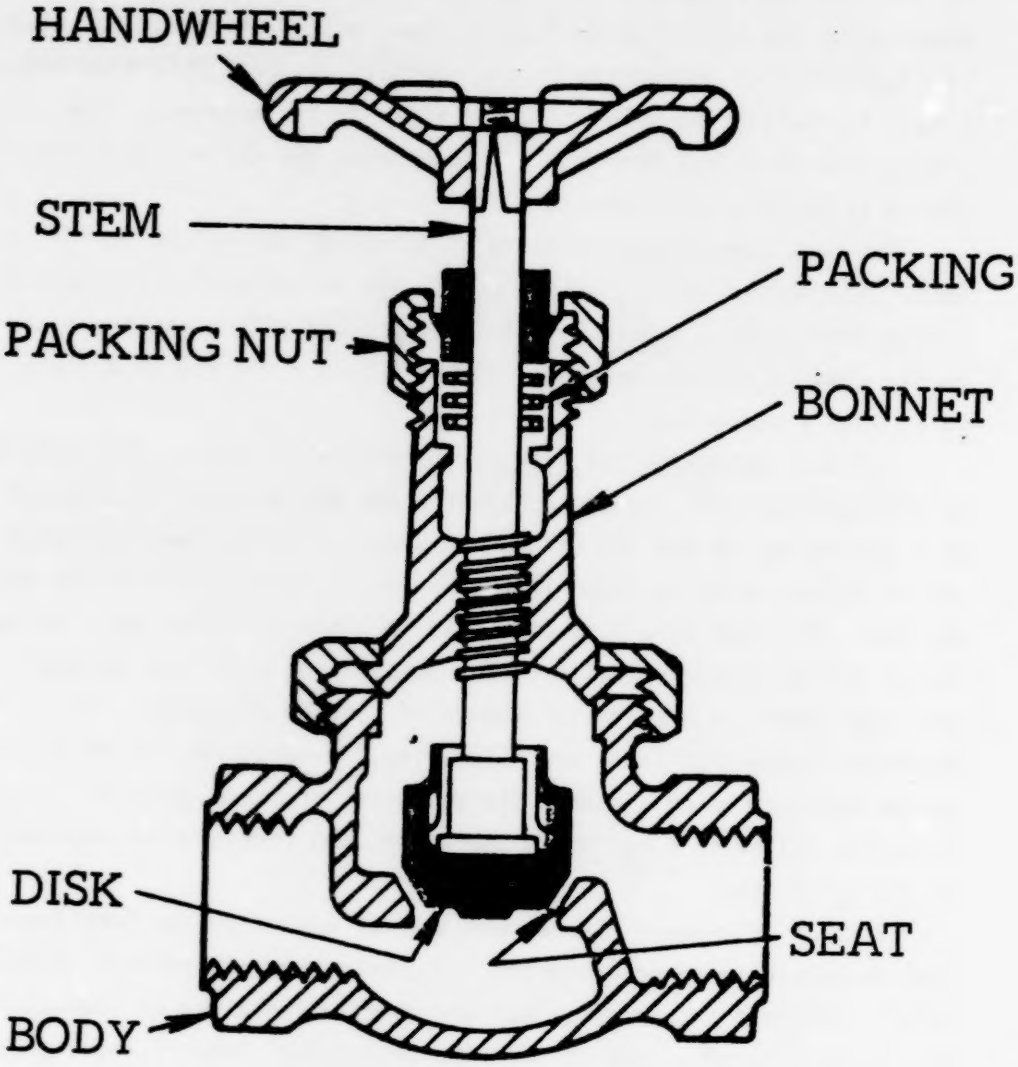
HANDWHEEL
STEM
PACKING
PACKING NUT
BONNET
DISK
SEAT
BODY

Figure 3-3. Globe Valve with Packed Seal[2]

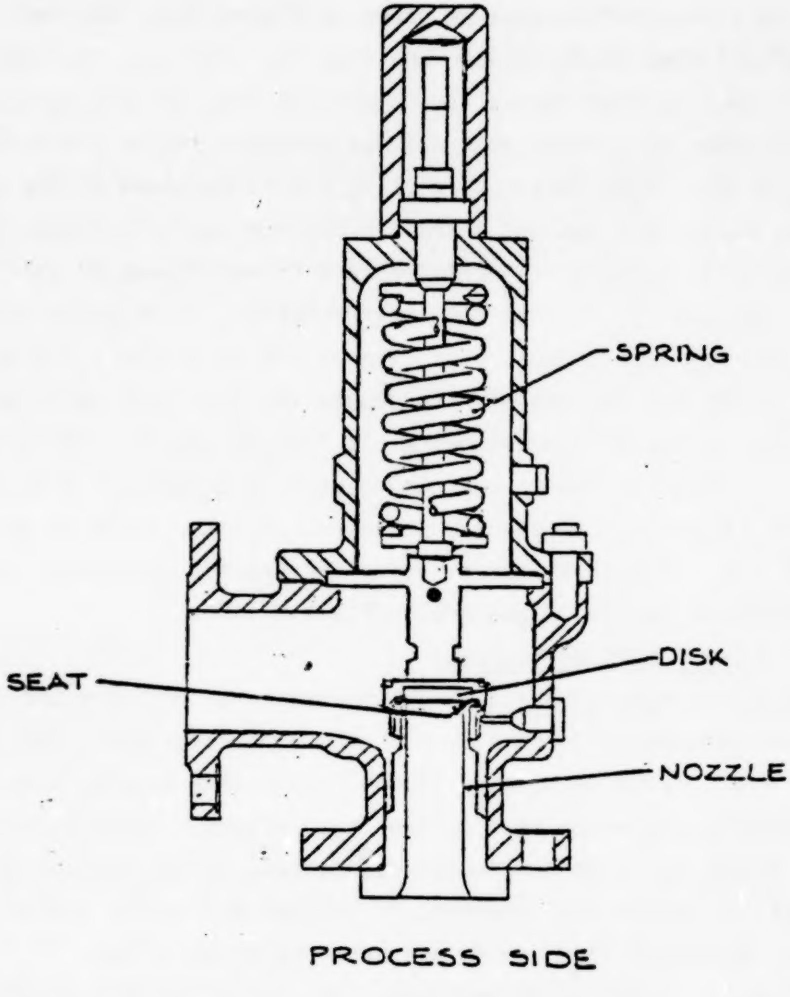
SPRING
DISK
SEAT
NOZZLE
PROCESS SIDE

Figure 3-4. Diagram of a Spring-Loaded Safety/Relief Valve[1]

that requires a seal to isolate the compressor interior gas from atmosphere. The possibility of a leak through this seal makes it a potential source of benzene emissions. In addition to having seal types like those used for pumps, centrifugal compressors can be equipped with a liquid-film seal as shown in Figure 3-5. The seal is a film of oil that flows between the rotating shaft and the stationary gland. The oil that leaves the compressor from the pressurized system side is under the system internal gas pressure and is contaminated with the gas. When this contaminated oil is returned to the open oil reservoir, process gas and entrained benzene can be released to atmosphere.

3.2.1.6 Agitators. Agitators are commonly used to stir or blend chemicals in organic chemical processes. Like pumps and compressors, agitators may leak organic chemicals at the point where the agitator shaft penetrates the vessel. Consequently, seals are required to minimize leakage of process materials from agitators. However, in the benzene operations that are known to utilize agitators, the agitated vessels operate at atmospheric pressure, so there would be no leakage at the seal. For this reason, agitators are not considered to be a significant source of benzene fugitive emissions.

3.2.2 Other Potential Sources

3.2.2.1 Process Drains. The operation of refinery and organic chemical process units entails draining condensate water and flushing water from process equipment. These drains also receive liquid leakage, spills, and water used to cool pump glands. Because most of these drains are open to atmosphere, benzene in the wastewater can be emitted to atmosphere. However, if leakage and spills are minimized, benzene emissions from drains are expected to be slight.

3.2.2.2 Sampling Connections. The operation of process units is checked periodically by routine analysis of feedstocks and products. To obtain representative samples for these analyses, sampling lines must first be purged. If this flushing liquid is not returned to the process, it could be drained onto the ground or into a process drain, where it would evaporate and release benzene to atmosphere.

3.2.2.3 Open-Ended Valves. Some valves are installed in a system so that they function with the downstream line open to atmosphere.

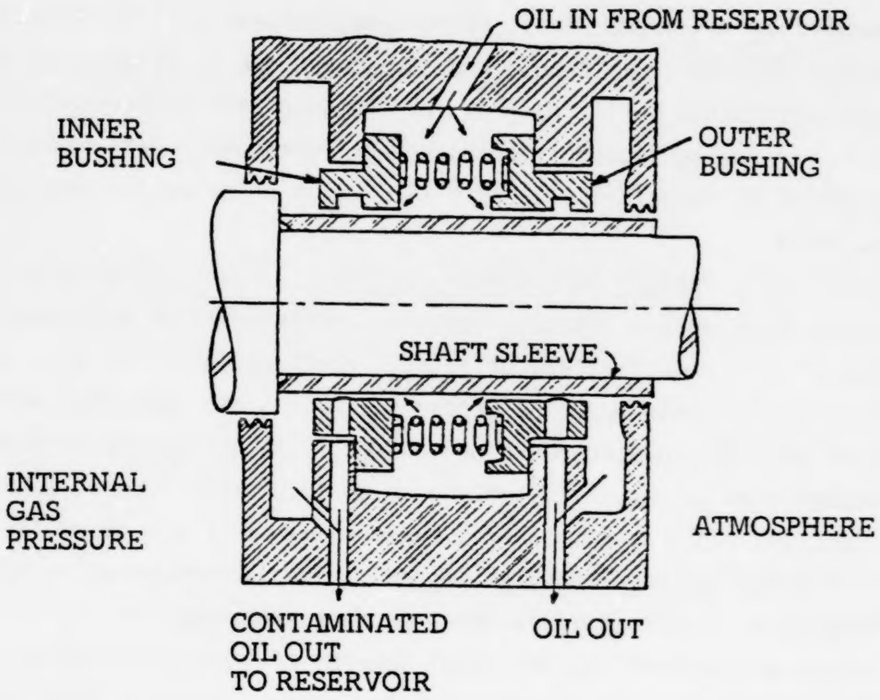
OIL IN FROM RESERVOIR
INNER BUSHING
OUTER BUSHING
SHAFT SLEEVE
INTERNAL GAS PRESSURE
ATMOSPHERE
CONTAMINATED OIL OUT TO RESERVOIR
OIL OUT

Figure 3-5. Liquid-Film Compressor Shaft Seal[3]

Examples are purge valves, drain valves, and vent valves. A faulty valve seat or incompletely closed valve would result in leakage through the valve and benzene emissions to atmosphere.

3.2.2.4 Wastewater Separators. Contaminated wastewater can originate from several sources including, but not limited to, leaks, spills, pump and compressor seal cooling and flushing, sampling, equipment cleaning, stripped sour water, desalter water effluent, and rain runoff. Contaminated wastewater is collected in the process drain system and directed to the wastewater treatment system where oil is skimmed in a separator, and the wastewater undergoes additional treatment as required. If it is present, benzene will be emitted wherever wastewater is exposed to atmosphere due to evaporation of benzene contained in the wastewater. As such, the primary emission points include surfaces of forebays and separators. Data are not available to characterize uncontrolled emission rates for wastewater separators.

3.2.2.5 Product Accumulator Vessels. Product accumulator vessels include overhead and bottoms receiver vessels utilized with fractionation columns, and product separator vessels utilized in series with reactor vessels to separate reaction products. Accumulator vessels can be vented directly to atmosphere or indirectly to atmosphere through a blowdown drum or vacuum system. When an accumulator vessel contains benzene and vents to atmosphere, benzene emissions can occur.

3.2.2.6 Vacuum-Producing Systems. The vacuum-producing systems attendant to vacuum distillation and other processes (including Sulfolane aromatic extraction) are potential sources of atmospheric emissions of benzene. Two types of vacuum-producing systems could be used for these processes:

- Steam ejectors with contact condensers.
- Steam ejectors with surface condensers.

In the contact condenser, condensable organics and steam from the vacuum still and the jet ejectors are condensed by intimately mixing with cold water. The condensable organics and water vapor flow to a condenser hot well. Benzene in the hot well can be evaporated and emitted to atmosphere. Any benzene that is not condensed in the barometric condenser can also be emitted directly to atmosphere. In a surface condenser, non-condensables and process steam from the vacuum still, mixed with steam from the jets, are condensed by cooling water in heat exchangers. These potential pollutants, therefore, do not come in contact with the cooling water. Again, any benzene that is not condensed may be emitted to atmosphere.

3.2.2.7 Cooling Towers. Cooling towers dissipate heat to atmosphere from the recirculating water that in turn is used to remove heat from such process equipment as reactors, condensers, and heat exchangers. If a leak in the process equipment occurs and if the equipment is operating at a pressure higher than that of the recirculating water, process material can be entrained in the water stream. This material can be evaporated and released to atmosphere from the cooling tower, making it a potential source of benzene emissions. Another source of emissions is the use of benzene-contaminated process water as a cooling water source. Uncontrolled emission data are not available for cooling towers.

3.2.2.8 Process Unit Turnarounds. Process units, such as reactors and fractionators, are periodically shut down and emptied for internal inspection and maintenance. The process of unit shutdown, repair or inspection, and start-up is termed a unit turnaround. Purging the contents of a vessel to provide a safe interior atmosphere for workmen is termed a vessel blowdown.

In a typical process unit turnaround, the liquid contents are pumped from the vessel to some available storage facility. The vessel is then depressurized, flushed with water, steam, or nitrogen, and ventilated. Depending on the facility configuration, the vapor content of the vessel may be vented to a fuel gas system, flared, or released directly to atmosphere. When vapors are released directly to atmosphere with potential benzene emissions, it is through a knock-out pot, which removes condensable benzene, and a blowdown stack, which is usually remotely located to ensure that combustible mixtures will not be released within the facility. Data are not available to characterize uncontrolled emission rates for process unit turnarounds.

3.2.2.9 Safety/Relief Valve Discharges. Safety/relief valves are designed to release a product material from distillation columns, pressure vessels, reactors, and other pressurized systems during emergency or upset conditions. Release of material containing benzene makes this equipment an emission source. The frequency and duration of releases, however, are dependent on the operating conditions of the particular plant, and wide operational variations between plants can occur.

3.3 MAGNITUDE OF BENZENE EMISSIONS FROM REFINING AND ORGANIC CHEMICAL PRODUCTION OPERATIONS

Data are limited on the measurement of benzene fugitive emissions from sources in the refining and organic chemical industries. However, recent testing efforts have generated a great deal of information on VOC emissions from refining operations. Refinery benzene fugitive emissions are assumed to be similar to the refinery VOC emissions for light liquid service equipment because of their similar vapor pressures. It is straightforward, therefore, to estimate refinery benzene fugitive emissions from these data. Since the majority of benzene fugitive emissions in the organic chemical industry originates from equipment handling benzene and benzene-containing organic streams, the emission factors developed from the refinery data should apply to organic chemical industry sources as well. Table 3-1 presents VOC emission factors for refining and organic chemical industry sources. Benzene emissions can be related to these VOC emission factors if it is assumed that the weight percent benzene in the gaseous emissions from a leaking piece of equipment is equivalent to the weight percent benzene in the product stream being handled by the equipment.

To illustrate the usage of these factors, benzene emissions were estimated for an example medium-sized production operation. Table 3-2 represents an average number of pieces of equipment handling benzene in a chlorobenzene production unit, a reformate benzene extraction unit, or a linear alkylbenzene production unit. The number of pieces of equipment multiplied by the appropriate emission factor from Table 3-1 yields the total benzene fugitive emissions for each type of equipment.

Table 3-1. ESTIMATED EMISSION FACTORS FOR NONMETHANE HYDROCARBONS FROM REFINING AND ORGANIC CHEMICAL INDUSTRY SOURCES

Source Type	Emission Factor Estimate[a] (Kg/hr - sources)
Pumps	0.12[e]
Pipeline Valves	
a. Gas/Vapor Streams	0.021
b. Liquid Streams	0.010[e]
Safety/Relief Valves[b]	0.16
Flanges	0.00026
Compressors	0.44
Process Drains	0.032
Sampling Connections	0.015[c]
Open-Ended Valves	0.0032[c]
Wastewater Separators	NA
Vacuum-Producing Systems	NA
Cooling Towers	Negligible
Process Unit Turnarounds	NA
Product Accumulator Vessel Vents	1.23[d]
Safety/Relief Valve Discharges	NA

NA - No factor available.

[a] From Reference 4 except where otherwise noted.

[b] Gas Service only.

[c] This factor was derived by the following equation:

$$\frac{\text{Kg VOC/hour}}{\begin{array}{c}\text{Sampling}\\ \text{Connections}\end{array}} = \frac{1.04\ \text{Kg VOC}}{\begin{array}{c}1000\ \text{Bbl refinery}\\ \text{throughput}\end{array}} \left(\begin{array}{c}\text{Purge}\\ \text{Loss,}\\ \text{See}\\ \text{Ref. 5}\end{array}\right) + \frac{\begin{array}{c}\text{sampling}\cdot\\ 86.4\ \text{connections}\end{array}}{\begin{array}{c}1000\ \text{Bbl/hour}\\ \text{refinery throughput}\end{array}} \left(\begin{array}{c}\text{From}\\ \text{Ref. 6}\end{array}\right)$$

+ 0.0032 Kg/hour for one open-ended valve (Seat Leakage, see Ref. 7) = 0.015 Kg/hour

[d] From Reference 8

[e] Emission factor for refinery equipment in light liquid service.

Table 3-2. ESTIMATED BENZENE EMISSIONS FROM AN AVERAGE PLANT[7]

Equipment Type[a]	Number of Pieces Handling 10 or More Weight Percent Benzene	Uncontrolled Benzene Emission[e] (kg/hr)
Pumps	15	1.80
Pipeline Valves		
Gas	91	1.91
Liquid	168	1.68
Safety/Relief Valves	9	1.44
Open-Ended Valves[b]		
Gas	9	0.22
Liquid	96	1.27
Sample Connections[c]	26	0.39
Flanges	600	0.16
Drains	15	0.48
Totals	1,003[d]	9.35

[a] Wastewater separators, vacuum-producing systems, process unit turnarounds, cooling towers and safety/relief valve discharges have been excluded due to lack of emission factors.

[b] Uncontrolled benzene emissions include emissions for pipeline valves and open-ended valves: gas = 0.0242 kg/hr per open-ended valve and liquid = 0.0132 kg/hr per open-ended valve.

[c] Number of sample connections is 25 percent of the number of open-ended valves.

[d] Total equipment excludes sample connections since they are included in the total number of open-ended valves.

[e] This assumes 100 percent benzene in the equipment.

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4.0 EMISSION CONTROL TECHNIQUES

4.1 INTRODUCTION

As identified in Chapter 3, there are several categories of potential sources of benzene fugitive emissions in refining and organic chemical operations. These sources include: (1) the cumulative total of small continuous leaking emission sources caused by seal leakage in pumps, valves, flanges, safety/relief valves, agitators, and compressors, (2) continuous emissions from the operation of vacuum-producing systems, drains, wastewater separators, and cooling towers, and (3) intermittent emissions from the operation of safety/relief valves, product accumulator vessel vents, sampling connections, open-ended valves, and process unit turnarounds.

Three basic control techniques can be applied to reduce benzene fugitive emissions from these potential sources. These techniques are as follows:

- Leak detection and repair programs in which fugitive sources are located and repaired at regular intervals.
- Preventive programs in which potential fugitive sources are eliminated by either retrofitting with specified controls or replacement with leakless equipment.
- Process modifications that reduce or eliminate benzene fugitive emissions by reducing or eliminating the use of benzene in production operations.

This chapter will discuss these control techniques and their effectiveness in reducing benzene fugitive emissions. Technical aspects of retrofitting specified controls and leakless equipment for the industry will also be discussed.

Four of the sources described in the previous chapter are not included in this discussion of emission control techniques — wastewater separators, cooling towers, process unit turnarounds, and agitators. No reliable data on emission rates and control techniques are available for cooling towers and process unit turnarounds, so these sources have not been included in this chapter. Wastewater separators are also not included because emission information for controlled and uncontrolled operations is not available. Agitators are not considered to be a significant source of benzene fugitive emissions. As stated in Chapter 3, agitated vessels in benzene operations operate at atmospheric pressure; consequently, no leakage is expected at the seal. These sources may be addressed in the future.

4.2 LEAK DETECTION AND REPAIR PROGRAMS

The types of equipment that have the potential to be benzene fugitive emission sources (i.e., pumps, valves, etc.) have been identified and discussed in Chapter 3. When such a piece of equipment develops a leak, the leak can be detected by using a portable VOC detector (performance criteria for the instrument and a description of the leak testing methods are given in Appendix D). When the leak has been located, it can be repaired through repair procedures, such as tightening the packing for valves.

Potential benzene fugitive emission sources at a given plant can be monitored at regular intervals with the portable detector, and the identified leaks can be repaired within a specified time limit. This approach is referred to as a leak detection and repair program, and it may be used to effect various control efficiencies depending on the action level (VOC concentration in parts per million by volume that defines a leak), leak detection interval, and allowable repair time specified.

Recently developed data can be used to predict the potential number of leaks from the various equipment types.[1] For example, Table 4-1 presents data on the percentage of pieces of equipment that are predicted to be found leaking at various action levels during an initial source screening survey.

Table 4-1 PERCENTAGE OF SOURCES PREDICTED TO BE LEAKING IN AN INDIVIDUAL COMPONENT SURVEY[1]

Equipment Type[a]	Predicted Percent of Sources Leaking[b]			
	>100,000ppmv	>50,000ppmv	>10,000ppmv	>1000ppmv
Pumps	6	9	23	41
Pipeline Valves				
a. Gas[c]	4	5	10	22
b. Liquid	2	4	12	25
Safety/Relief Valves	1	2	8	21
Pipeline Flanges	0	0	0	2
Compressors	6	10	33	68
Process Drains	0	1	4	10

[a] Data are not available for open-ended valves, sampling connections, wastewater separators, vacuum-producing systems, and cooling towers. This type of information would not be appropriate for process unit turnarounds, product accumulator vessel vents, and safety/relief valve over-pressure.

[b] The technical feasibility of repairing leaks in the 1000 - 10,000 ppm range and achieving an overall emission reduction has not been demonstrated in field testing.

[c] Valves in gas service contain process fluid in the gaseous state.

4.2.1 Definition of a Leak

In order to develop a leak detection plan for equipment leaks, an equipment leak must first be defined. The choice of the action level for defining a leak is influenced by several considerations. First, the percent of total mass emissions that can potentially be controlled by the leak detection and repair program can be affected by varying the action level. Table 4-2 gives the percent of total mass emissions affected at various action levels for a number of equipment types. From the table, it can be seen that, in general, a low action level results in larger potential emission reductions. However, the choice of an appropriate leak definition is limited by the ability to repair leaking components.

The ability to repair leaking equipment from above 10,000 ppm to below 10,000 ppm has been demonstrated in field testing.[2] This repair ability has not been demonstrated for a 1,000 ppm action level, however. Available data do not support the conclusion that repairing leaks in the 1,000 to 10,000 ppm range would result in an overall reduction in emissions.

The nature of repair techniques for pipeline valves, for instance, is such that attempts to repair leaks below a certain level by tightening the packing gland may result in an increase in emissions. In practice, valve packing material can become hard and brittle after extended use. As the packing loses its resiliency, the valve packing gland must be tightened to prevent loss of product to atmosphere. Excessive tightening, however, may cause cracks in the packing, thus exacerbating the leak rate.

4.2.2 Inspection Interval

A leak detection plan may include annual, quarterly, monthly, or even weekly inspections. The length of time between inspections should depend on the expected occurrence and recurrence of leaks after a piece of equipment has been checked and/or repaired. This interval can be related to the type of equipment and service conditions, and different intervals can be specified for different pieces of equipment.

In the refinery VOC leak Control Technique Guideline (CTG) document[3], the recommended leak detection intervals are: annual -- pump seals,

Table 4-2. PERCENT OF TOTAL MASS EMISSIONS AFFECTED AT VARIOUS ACTION LEVELS[1]

Source Type	Percent of Mass Emissions Affected at this Action Level[a]			
	100,000 ppmv	50,000 ppmv	10,000 ppmv	1,000 ppmv[b]
Pumps	56	68	87	97
Pipeline Valves				
Gas[c]	85	92	98	99
Liquid	49	62	84	96
Safety/Relief Valves	19	33	69	91
Compressors	28	48	84	98
Drains	0	8	46	82

[a] These figures relate the action level to the percentage of total mass emissions that can be expected from sources with concentrations at the source greater than the action level. If these sources were instantaneously repaired to a zero leak rate and no new leaks occurred, then emissions could be expected to be reduced by this maximum theoretical efficiency.

[b] The technical feasibility of repairing leaks in the 1000 to 10,000 ppm range and achieving an overall emission reduction has not been demonstrated in field testing.

[c] Valves in gas service contain process fluid in the gaseous state.

pipeline valves in liquid service, and process drains; quarterly -- compressor seals, pipeline valves in gas service. and safety/relief valves in gas service; weekly -- visual inspection of pump seals; and no individual monitoring -- pipeline flanges and other connections, and safety/relief valves in liquid service. The choice of the interval affects the emission reduction achievable, since more frequent inspection will result in earlier detection and repair of leaking sources.

4.2.3 Allowable Repair Time

If a leak is detected, the equipment should be repaired within a certain time period. The allowable repair time should reflect an interest in eliminating a source of benzene emissions, but it should also allow the plant operator sufficient time to obtain necessary repair parts and maintain some degree of flexibility in overall plant maintenance scheduling. Once again, the determination of this allowable repair time will affect emission reductions by influencing the length of time that leaking sources are allowed to continue to emit benzene.

4.2.4 Visual Inspections

Visual inspections can be performed to detect evidence of liquid leakage from plant equipment. When such evidence is observed, the operator can use a portable VOC detector to measure the VOC concentration of the source. All liquid leaks will not necessarily result in a reading of greater than the action level.[3] In a specific application, visual inspections can be used to detect the failure of the outer seal of a pump double mechanical seal system. Observation of liquid leaking along the shaft indicates an outer seal failure and signals the need for seal repair.

4.2.5 Other Leak Detection Techniques

Other leak detection techniques have been proposed to supplement the individual component survey. These techniques include unit area surveys (walkthroughs) and fixed-point leak detection systems. In theory, these techniques allow the operator to reduce the number of components that must be individually surveyed and hence reduce leak detection labor requirements.

4.2.5.1 Unit Area Survey. A unit area survey entails measuring the ambient VOC concentration within a given distance, for example, one meter of all equipment located on ground and other accessible levels within a processing area. These measurements are performed with a portable VOC detector utilizing a strip chart recorder.

The instrument operator walks a predetermined path to assure total available coverage of a unit on both the upwind and downwind sides of the equipment, noting on the chart record the location in a unit where any elevated VOC concentrations are detected. If an elevated VOC concentration is recorded, the components in that area can be screened individually to locate the specific leaking equipment.

It is estimated that 50 percent of all significant leaks in a unit are detected by the walkthrough survey, provided that there are only a few pieces of leaking equipment, thus reducing the VOC background concentration sufficiently to allow for reliable detection.[4]

The major advantages of the unit area survey are that leaks from accessible leak sources near the ground can be located quickly and that the leak detection manpower requirements can be lower than those for the individual component survey. Some of the shortcomings of this method are that VOC emissions from adjacent units can cause false leak indications; high or intermittent winds (local meteorological conditions) can increase dispersion of VOC, causing leaks to be undetected; elevated equipment leaks are not detected; and additional effort is necessary to locate the specific leaking equipment (i.e., individual checks in areas where high concentrations are found).

4.2.5.2 Fixed-Point Monitoring Systems. The basic concept of the fixed-point monitoring system is that sampling-point devices can be installed at specific sites within a process area to monitor for leaks automatically. The ambient benzene concentration can be remotely and centrally indicated to the operator, who can respond appropriately when elevated levels are recorded. The monitoring sites would not include the entire area of the plant, but only areas where equipment handling benzene is located.

The approaches to leak detection with fixed-point monitors differ in the number and placement of the sample points and in the manner in which the sample is taken and analyzed. One approach is to establish the sample points near specific pieces of equipment, such as process pumps and compressors. A second approach is to establish the sample points in a grid pattern throughout the process area. When an elevated concentration is noted, the operator performs an individual component survey on equipment in that area to locate the leaking component. In addition to these variations in the location of the sampling points, different types of systems can be used. For example, the sampling can be done on-site or the samples can be collected at the site and then analyzed at a central location (an automatic sequential system).

One feature of the fixed-point monitor approach is that the location of the monitor and the type of sampling and analysis can be tailored to meet the requirements of individual plant sites and VOC. Fixed-point monitors have the capability to sample for benzene specifically by gas chromatography -- flame ionization detection (GC/FID) or infrared (IR) analysis. This allows the sources leaking benzene to be located more easily. However, this approach will require the use of a portable VOC detector to locate the leak, particularly if a gridded process-area monitoring approach is used. Leak detection efficiency for fixed-point monitoring systems is estimated to be 33 percent[5] for facilities with a small number of recurring leaks, provided that major leaking equipment has been repaired, reducing the benzene background concentration sufficiently to allow reliable detection.

The fixed-point monitoring approach can also be utilized to monitor the operation of individual pieces of equipment and detect control device failures that would result in leaks. In specific applications, the barrier fluid system of a double pump seal can be monitored with a sensing device to signal seal failure. Also, in cases where rupture disks are installed upstream of safety/relief valves, leakage through the disk can be monitored if pressure gauges and/or excess flow valves are installed between the disk and the valve.

4.2.6 Repair

When leaks are located by the leak detection methods described in this section, the leaking component can then be repaired or replaced. Many components can be serviced on-line. This is generally regarded as routine maintenance to keep operating equipment functioning properly. Equipment failure, as indicated by a leak not eliminated by servicing, requires isolation of the faulty equipment for either repair or replacement.

4.2.6.1 Pumps. Most critical service process pumps are backed up with a spare so that they can be isolated for repair. Of those pumps that are not backed up with spares, some can be corrected by on-line repairs (e.g., tightening the packing). However, most leaks that need correction require that the pump be removed from service for seal repair.

4.2.6.2 Valves. Most valve leaks can be reduced on-line by tightening the packing gland for valves with packed seals or by lubrication for plug valves, for example. Based on field observations, one refinery study assumed that 75 percent of leaking valves could be repaired on-line.[6]

Valves that need to be repacked or replaced to reduce leakage must be isolated from the process. Control valves, 6 to 8 percent of the total valves in benzene service in the refining and organic chemical industries,[4] can usually be isolated. Block valves, which are used to isolate or by-pass equipment, normally cannot be isolated. One refiner estimates that 10 percent of the block valves can be isolated.[7]

When leaking valves can be corrected on-line, repair servicing can be done immediately after detection of the leak. When the leaks can be corrected only by a total or partial shutdown, the temporary emissions could be larger than the continuous emissions that would result from not shutting down the unit until it was time for a shutdown for other reasons. Simple maintenance procedures, such as packing gland tightening and grease injection, can be applied to reduce emissions from leaking valves until a shutdown is scheduled. Leaks that cannot be repaired on-line can be repaired by drilling into the valve housing and injecting a sealing compound. This practice is growing in acceptance, especially for safety concerns.[8]

4.2.6.3 Flanges. One refinery field study noted that most flange leaks could be sealed effectively on-line by simply tightening the flange bolts.[6] For a flange leak that requires off-line gasket seal replacement, a total or partial shutdown of the unit would probably be required because most flanges cannot be isolated.

For many of these cases, there are temporary flange repair methods that can be used. Unless a leak is major and cannot be temporarily corrected, the temporary emission from shutting down a unit would probably be larger than the continuous emissions that would result from not shutting down the unit until time for a shutdown for other reasons.

4.2.6.4 Compressors. Compressors usually are in critical service but often spares are not provided. Consequently, the compressors would need to be bypassed, possibly by a partial or complete unit shutdown, so that repairs can be made. In most cases the shutdown for repair of the leaking seal and the subsequent startup will involve flaring the process stream until operations are stabilized. This can result in the temporary emissions being larger than the continuous emissions that would occur until the unit was shut down for other reasons.

4.2.7 Emission Control Effectiveness of Leak Detection and Repair

The control efficiency achieved by a leak detection and repair program is dependent on several factors, including the action level, the inspection frequency, and the allowable repair time.

Data are presented in Table 4-2 that show the expected fraction of total emissions from each type of source contributed by those sources with VOC concentrations greater than given action levels. If a leak detection and repair program resulted in repair of all such sources to 0 ppm, elimination of all sources over the action level between inspections, and instantaneous repair of those sources found at each inspection, then emissions could be expected to be reduced by the amount reported in Table 4-2. However, since these conditions are not met in practice, the fraction of emissions from sources with VOC concentrations over the action level represents the theoretical maximum reduction efficiency. The approach to estimation of emission reduction presented here is to reduce this theoretical maximum control efficiency by accounting quantitatively for those factors outlined above.

This approach can be expressed mathematically by the following equation:[9]

Reduction efficiency = A x B x C x D

Where:

A = Theoretical Maximum Control Efficiency = fraction of total mass emissions from sources with VOC concentrations greater than the action level (from Table 4-2).

B = Leak Occurrence and Recurrence Correction Factor = correction factor to account for sources which start to leak between inspections (occurrence) and for sources which are found to be leaking, are repaired and start to leak again before the next inspection (recurrence), including known leaks that could not be repaired.

C = Non-Instantaneous Repair Correction Factor = correction factor to account for emissions which occur between detection of a leak and subsequent repair, since repair is not instantaneous.

D = Imperfect Repair Correction Factor = correction factor to account for the fact that some sources which are repaired are not reduced to zero emission levels. For computational purposes, all sources which are repaired are assumed to be reduced to a 1000 ppm emission level.

An implicit assumption here is that the leak detection program detects all of the sources with VOC concentrations greater than the action level that are present at the time of the inspection. As an example of this technique, Table 4-3 gives values for the "B," "C" and "D" correction factors for various possible inspection intervals, allowable repair times, and action levels.

4.3 PREVENTIVE PROGRAMS

Another approach to reducing benzene fugitive emissions from chemical and refinery operations is to replace components with equipment which does not leak. This approach is referred to as a preventive program. This section will discuss the kinds of equipment that could be applied in such a program and the advantages and disadvantages of this equipment.

4.3.1 Pumps

As discussed in Chapter 3, pumps can be potential benzene fugitive emission sources because of leakage through the drive-shaft sealing

Table 4-3. EMISSION CORRECTION FACTORS FOR VARIOUS INSPECTION INTERVALS, ALLOWABLE REPAIR TIMES AND ACTION LEVELS[a] (Reference 9)

	Leak Occurrence and Recurrence Correction Factor[b]			Non-Instantaneous Repair Correction Factor[c]			Imperfect Repair Correction Factor[d]			
	Inspection Interval			Allowable Repair Time (Days)			Action Level (ppmv)			
Source	Yearly	Quarterly	Monthly	15	5	1	100,000	50,000	10,000	1,000[e]
Pumps	0.800	0.900	0.950	0.979	0.993	0.999	0.969	0.961	0.923	0.876
Pipeline Valves										
Gas[f]	0.800	0.900	0.950	0.979	0.993	0.999	0.997	0.996	0.993	0.986
Liquid	0.800	0.900	0.950	0.979	0.993	0.999	0.984	0.975	0.944	0.898
Safety/Relief Valves[g]	0.800	0.900	0.950	0.979	0.993	0.999	0.989	0.987	0.976	0.951
Compressors	0.800	0.900	0.950	0.979	0.993	0.999	0,983	0.984	0,970	0,946
Drains	0.800	0.900	0.950	0.979	0.993	0.999	---	0.864	0.906	0.868

[a] Note that these correction factors taken individually do not correspond exactly to the overall emission reduction obtainable by a leak detection and repair program. The overall effectiveness of the program is determined by the product of all correction factors.

[b] Values are assumed and account for sources that start to leak between inspections (occurrence) and for sources that are found to be leaking, are repaired, and start to leak again before the next inspection (recurrence), including known leaks that could not be repaired.

[c] Accounts for emissions that occur between detection of a leak and subsequent repair.

[d] Accounts for the fact that some sources that are repaired are not reduced to 0 ppm emission levels. The average repair factors at 1000 ppmv are assumed.

[e] The technical feasibility of repairing leaks in the 1000-10,000 ppm range and achieving an overall emission reduction has not been demonstrated in field testing.

[f] Valves in gas service carry process fluids in the gaseous state.

[g] Gas service only.

mechanism. This kind of leakage can be reduced to a negligible level through the installation of improved shaft sealing mechanisms, such as dual mechanical seals, or it can be eliminated entirely by installing sealless pumps.

4.3.1.1 Dual Mechanical Seals. By design, dual mechanical seals (double or tandem) have a chamber between the two seal faces that either is flushed with a circulating sealing fluid that allows control of the conditions under which the seal operates, or is flooded with a barrier fluid. Double mechanical seal systems have two seals in a back-to-back arrangement providing an enclosed cavity. The barrier fluid between the two seals is circulated through the cavity to lubricate and cool the seals. The barrier fluid typically is maintained at a pressure greater than the pump stuffing box pressure (Figure 4-1) so that any leakage between the seals would be from the barrier fluid to the process fluid. Consequently, no benzene would be emitted to atmosphere as long as the double mechanical seal system is operating properly. Field screening has shown that the magnitude of emissions from new pumps equipped with double mechanical seals is negligible as long as the integrity of the seals is maintained. Double seals do fail after extended periods of use, however, and can develop leaks.[10]

Tandem mechanical seal systems have two mechanical seals in a front-to-back arrangement. Like double seals, tandem seal systems utilize a barrier fluid; however, the barrier fluid pressure is maintained at a pressure lower than the pump stuffing box pressure. In this arrangement, there is the possibility of leakage of the process fluid into the barrier fluid. Leakage into the barrier fluid can be controlled by either (1) connecting the barrier fluid degassing system to a control device (i.e., enclosed combustion or vapor recovery) with a closed vent system or (2) continuously replacing the fluid with fresh barrier fluid and properly disposing of the contaminated barrier fluid. One company, however, has reported mechanical problems associated with lubrication of the outside seal, which cannot operate in a "dry" state. When the outside seal fails, it may not be detected until the inside seal fails, causing release of product. In addition, a bearing

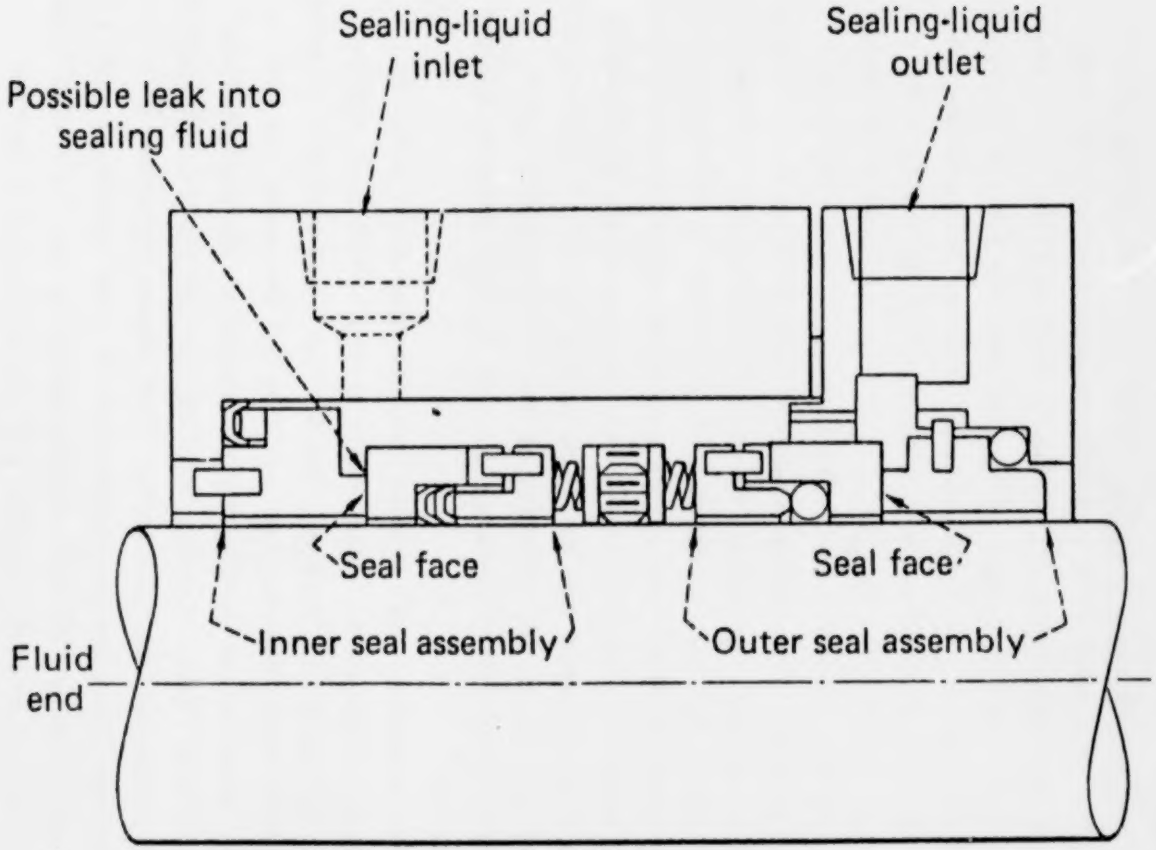
Possible leak into sealing fluid
Sealing-liquid inlet
Sealing-liquid outlet
Seal face
Seal face
Inner seal assembly
Outer seal assembly
Fluid end

Figure 4-1. Double Mechanical Seal[4]

failure, which usually affects the entire pump shaft, can damage or destroy both tandem seals so that their effectiveness in reducing emissions is no more than a single mechanical seal.[10]

The barrier fluid system between the dual seals may be a circulating system, or it may rely on convection to circulate fluid within the system. While the main function of the barrier fluid is to keep the pumped fluid away from the environment, it can serve other functions as well. A barrier fluid can provide temperature control in the stuffing box. Furthermore, it can protect the pump seals from the atmosphere, as in the case of pumping easily oxidizable materials that form abrasive oxides or polymers upon exposure to air. A wide variety of fluids can be used as barrier fluids. Some of the more common ones which have been used are water (or steam), glycols, methanol, oil, and heat transfer fluid. In cases in which product contamination cannot be tolerated, clean product, a product additive, or a product diluent may also be used.

Mechanical seals, single or dual, have limits on their applicability. They can be used only on shafts with a rotary motion. Also, the maximum service temperature is usually limited to less than 260°C.[7] In spite of these limitations, dual mechanical seals can be used in most new pump applications.[4] Dual mechanical seals can also be retrofitted on many pumps that were designed for single mechanical seals and packed seals. In most cases, the retrofit involves the engineering required for selection of a suitable dual seal assembly, purchase of the seal, and installation. For some existing packed and single mechanical seal pumps, however, the entire pump may have to be replaced because the existing pump casing will not adequately house a dual mechanical seal assembly. Data from industrial sources indicate that this situation may occur for about 10 percent of all pumps in benzene service.[12]

4.3.1.2 Sealless Pumps. The sealless or canned-motor pump is designed so that the pump casing and rotor housing are interconnected. As shown in Figure 4-2, the impeller, motor rotor, and bearings are completely enclosed and all seals are eliminated. A small portion of process fluid is pumped through the bearings and rotor to provide lubrication and cooling.

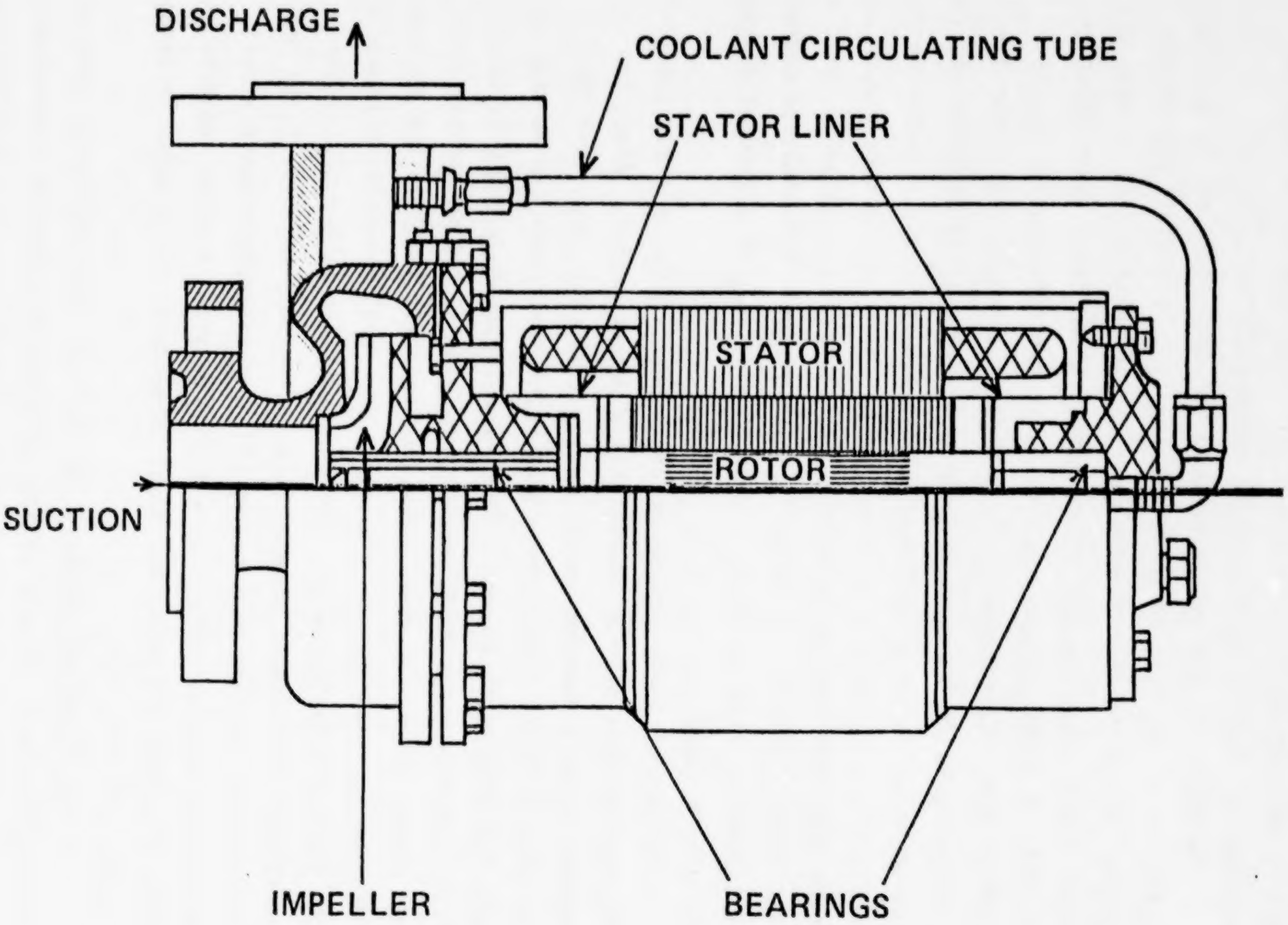
DISCHARGE
COOLANT CIRCULATING TUBE
STATOR LINER
STATOR
ROTOR
SUCTION
IMPELLER
BEARINGS

Figure 4-2. Seal-less Canned Motor Pump

Standard single-stage canned-motor pumps are available for flows up to 160 cubic meters per second and heads up to 76 meters. Two-stage units are also available for heads up to 183 meters. Canned-motor pumps are widely used in applications where leakage is a problem.[13]

The main design limitation of these pumps is that only clean process fluids may be pumped without excessive bearing wear. Since the process liquid is the bearing lubricant, abrasive solids cannot be tolerated. Also, there is no potential for retrofitting mechanical or packed seal pumps for sealless operation. Use of these pumps in existing plants would require that existing pumps be replaced.

4.3.2 Valves

As in the case of pumps, valves can be sources of benzene fugitive emissions because of leakage through the packing used to isolate process fluids from atmosphere (see Chapter 3). If the valve stem can be isolated from the process fluid, however, this emission source can be eliminated. There are two types of valve designs in which the stem is so isolated, and potential for leakage around the stem is thus eliminated. These valve types are the diaphragm valve and the sealed bellows valve.

4.3.2.1 Diaphragm Valves. The general configuration of a diaphragm valve is shown in Figure 4-3. The process fluid is isolated from the valve stem by a flexible elastomer diaphragm, thus eliminating the potential for leakage around the stem. The position of the diaphragm is regulated by a plunger, which is in turn controlled by the stem. The stem may be actuated manually or automatically by standard hydraulic, pneumatic, or electric actuators.

These valves have excellent corrosion resistance characteristics and are reported to perform well in control valve situations with minimal maintenance.[14] The design problems associated with diaphragm valves are the temperature and pressure limitations of the elastomer used for the diaphragm. It has been found that temperature extremes tend to damage or destroy the diaphragm in the valve. Also, operating pressure constraints may limit the application of diaphragm valves to low pressure operations.[15]

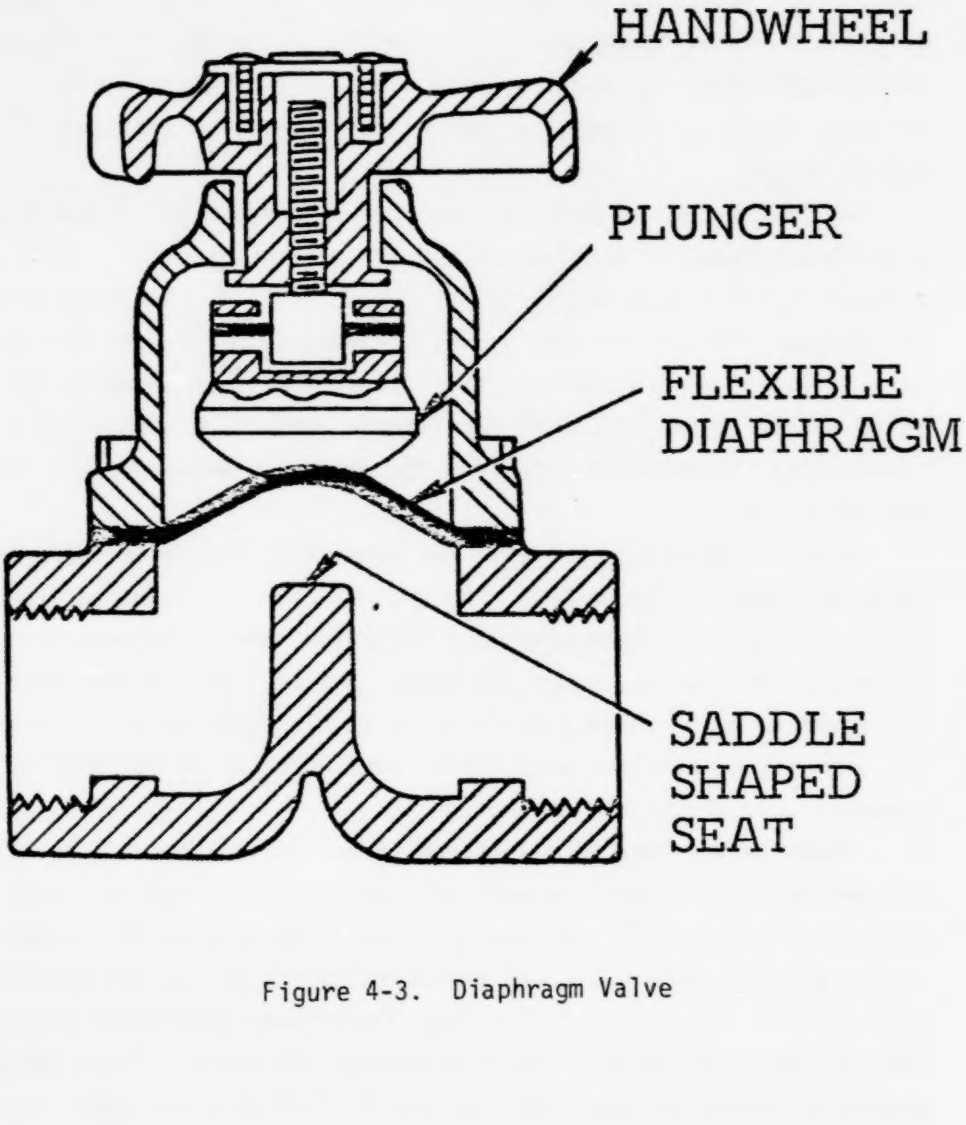
HANDWHEEL
PLUNGER
FLEXIBLE DIAPHRAGM
SADDLE SHAPED SEAT

Figure 4-3. Diaphragm Valve

4.3.2.2 Sealed Bellows Valves. The basic design of a sealed bellows valve is shown in Figure 4-4. The stem in this type of valve is isolated from the process fluid by a metal bellows. The bellows is generally welded to the bonnet and disk of the valve, thereby effecting isolation of the stem.

There are two main disadvantages to these valves. First, they are only available in globe and gate valve configurations. Second, the crevices of the bellows may be subject to corrosion under severe conditions if the bellows alloy is not carefully selected.

The main advantage of these valves is that they can be designed to withstand high temperatures and pressures so that leak-free service can be provided at operating conditions beyond the limits of diaphragm valves.

4.3.3 Safety/Relief Valves

4.3.3.1 Rupture Disks. A rupture disk can be used upstream of a safety/relief valve so that under normal conditions it seals the system tightly but will break when its set pressure is exceeded, at which time the safety/relief valve will relieve the pressure. Figure 4-5 is a diagram of a rupture disk and safety/relief valve installation. The installation is arranged to prevent disk fragments from lodging in the valve and preventing the valve from being reseated if the disk ruptures. It is important that no pressure be allowed to build in the pocket between the disk and the safety/relief valve; otherwise, the disk will not function properly. A pressure gauge and bleed valve can be used to prevent pressure buildup. With the use of a pressure gauge, it can be determined whether the disk is properly sealing the system against leaks. It is also necessary to install a block valve upstream of the rupture disk so that the disk can be isolated and repaired on-line without shutting down the unit. Alternately, to prevent possible overpressure while using a block valve, a parallel system of relief valves and rupture disks can be installed so that one rupture disk/relief valve is in operation while the other is being repaired.

Use of a rupture disk upstream of a safety/relief valve would eliminate leaks due to improper seating and simmering of the relief

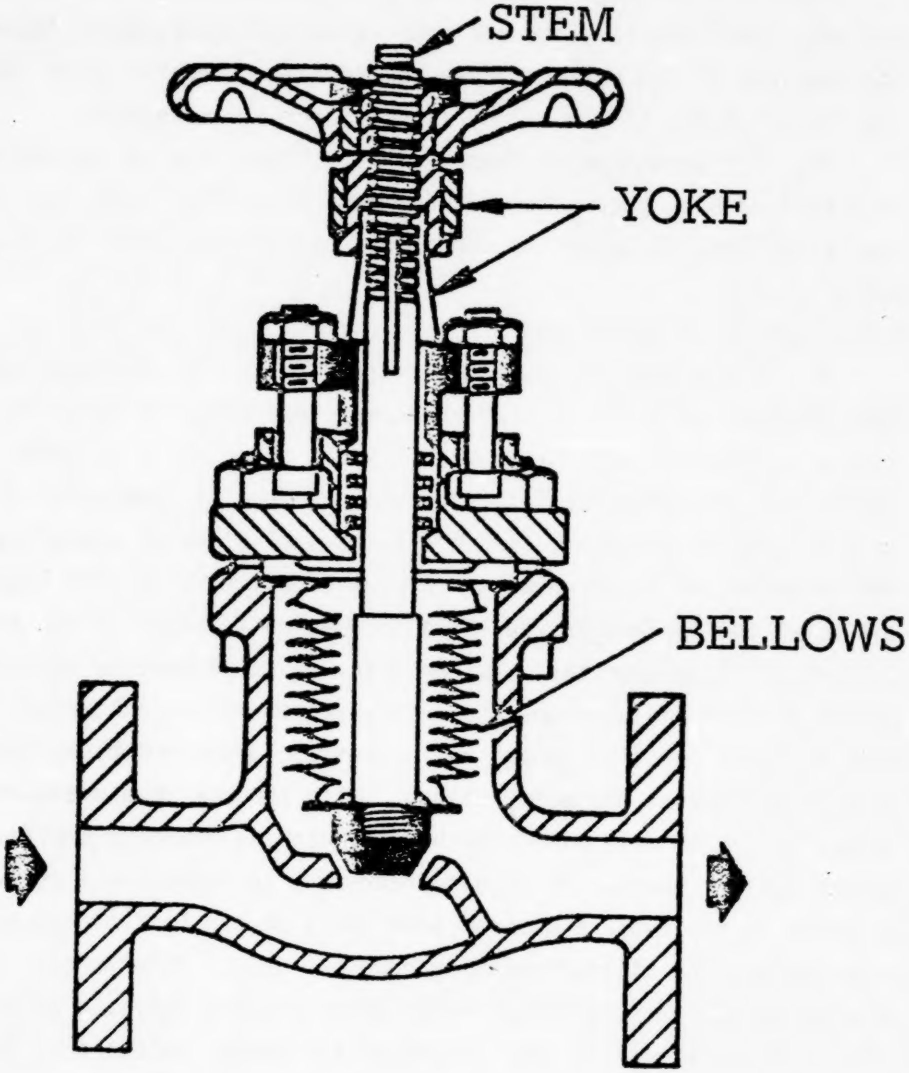
STEM
YOKE
BELLOWS

Figure 4-4. Sealed Bellows Valve

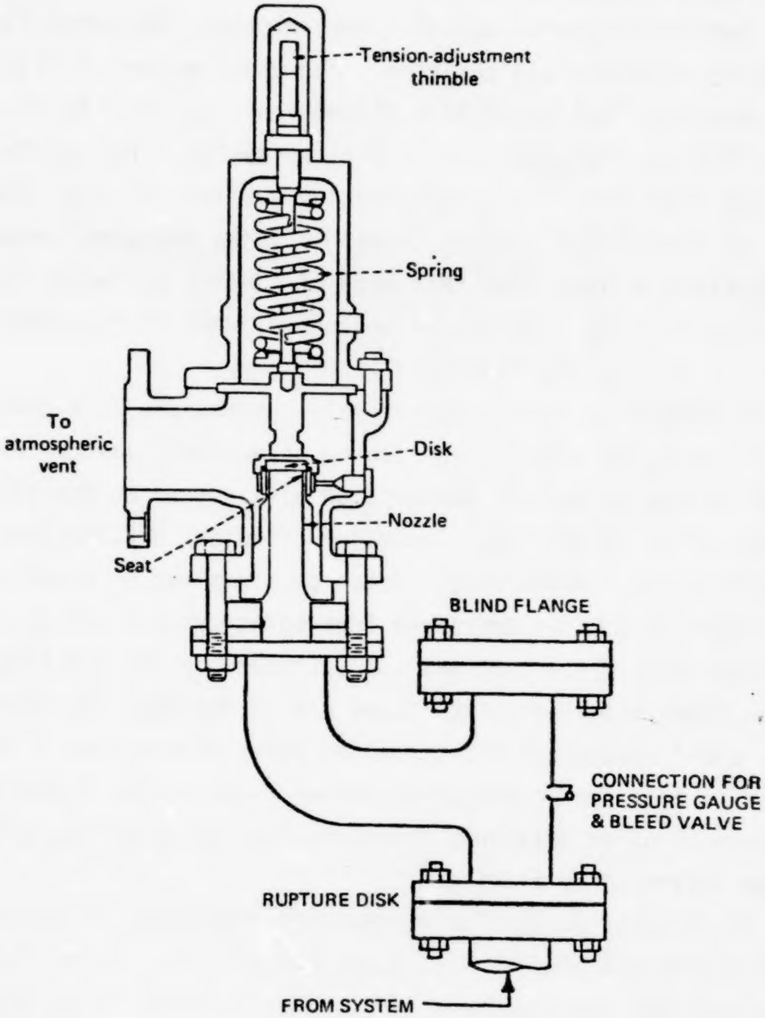
Tension-adjustment thimble
Spring
To atmospheric vent
Disk
Nozzle
Seat
BLIND FLANGE
CONNECTION FOR PRESSURE GAUGE & BLEED VALVE
RUPTURE DISK
FROM SYSTEM

Figure 4-5. Rupture Disk Installation Upstream of a Safety/Relief Valve[4]

valve. Also, the disk can extend the life of a safety/relief valve by protecting it against system materials that could be corrosive and thereby cause seal degradation.

4.3.3.2 Closed-Vent Systems. A closed-vent system can be used to collect and dispose of gaseous benzene emissions resulting from the relieving of safety/relief valves. Emissions from safety/relief valve overpressure are typically intermittent, and their flow rates during major upsets can be large. The usual method of disposing of these gases, if collected in a closed vent, would be by flaring. Figure 4-6 is a diagram of a dual-flare system. The smaller flare operates more efficiently with routine smaller exhaust. The larger flare is normally on standby to handle large emergency exhausts. It is important to note that this type of control system would control intermittent large releases of benzene as well as the continuous small emissions from safety/relief valve leakage.

By connecting safety/relief valve discharges to a closed-vent and flare system, their emissions can be effectively controlled. The effectiveness of benzene destruction will depend on the flare design and turn-down capability. The major technical difficulties with flares occur in manifolding. These problems may be especially important in existing plants if emissions from safety/relief valves are manifolded to an existing flare that was not designed for the additional flow. In new plant situations, the flare can be designed for expected flow rates and frequency of safety/relief valve discharges. Finally, off-gases from some chemical processes could not be flared due to the presence of other hazardous compounds such as chlorine, which would not be destroyed by flaring.

At present, no conclusive data are available on flare efficiency. Calculations and limited test data show efficiencies ranging from 60 percent for low flow to a large flare to 90 to 99 percent for large flow to a large flare.[16-19] The presence of saturated organics or aromatic compounds may decrease efficiency since such compounds are not easily oxidized.

4.3.4 Open-Ended Valves

Caps, plugs, and double block and bleed valves are devices for closing off the ends of valves and pipes. When installed downstream

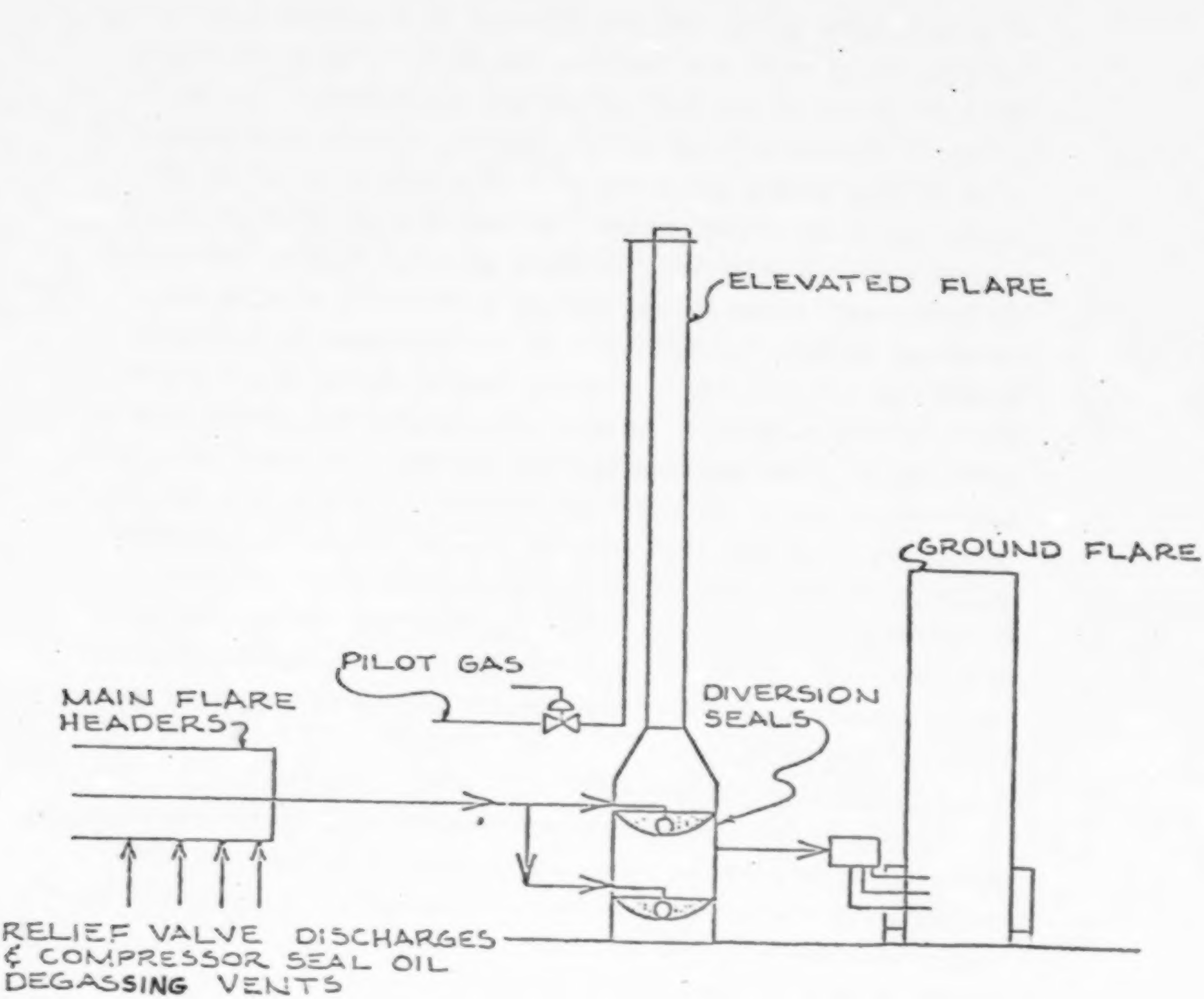
ELEVATED FLARE
GROUND FLARE
PILOT GAS
MAIN FLARE HEADERS
DIVERSION SEALS
RELIEF VALVE DISCHARGES & COMPRESSOR SEAL OIL DEGASSING VENTS

Figure 4-6. Simplified Closed-Vent System with Dual Flares[4]

of an open-ended valve, they are effective in preventing leaks through the seat of the valve from reaching atmosphere. Open-ended valves, about 20 percent of the total valves handling benzene,[20] are used mostly in intermittent service for sampling, venting, or draining. If a cap or plug is used downstream of a valve when it is not in use, benzene emissions can be reduced. No test data are available to support a control efficiency for these devices. However, the control efficiency will depend on such factors as frequency of valve use, valve seat leakage, and material that may be trapped in the pocket between the valve and cap or plug and lost on removal of the cap or plug. For the purposes of emission calculations, 100 percent control efficiency of these emissions has been assumed. The installation of a cap, plug, or second valve does not prevent the leakage that may occur through the valve stem seal. The attachment of a second valve downstream of the open-ended valve provides a double block and bleed arrangement. In this system, it is important that the upstream valve be closed first. Otherwise, product will remain in the line between the valves, and expansion of this product will cause leakage through the valve stem seals.

4.3.5 Closed-Loop Sampling

A frequent operation in most refining and organic chemical production operations is to withdraw a sample of material from the process for analysis. To ensure that the sample is representative, purging of the sample lines and/or sample container is often required. If this purging is done to atmosphere or to open drains, or if there are incidental handling losses, benzene emissions can result. A closed-loop sampling system is designed so that the purged VOC is returned to the system or sent to a closed disposal system and so that the handling losses are minimized. Figure 4-7 gives two examples of closed-loop sampling systems where the purged VOC is flushed from a point of higher pressure to one of lower pressure in the system and where sample-line dead space is minimized. Other sampling systems are available that utilize partially evacuated sampling containers and require no line pressure drop.[21]

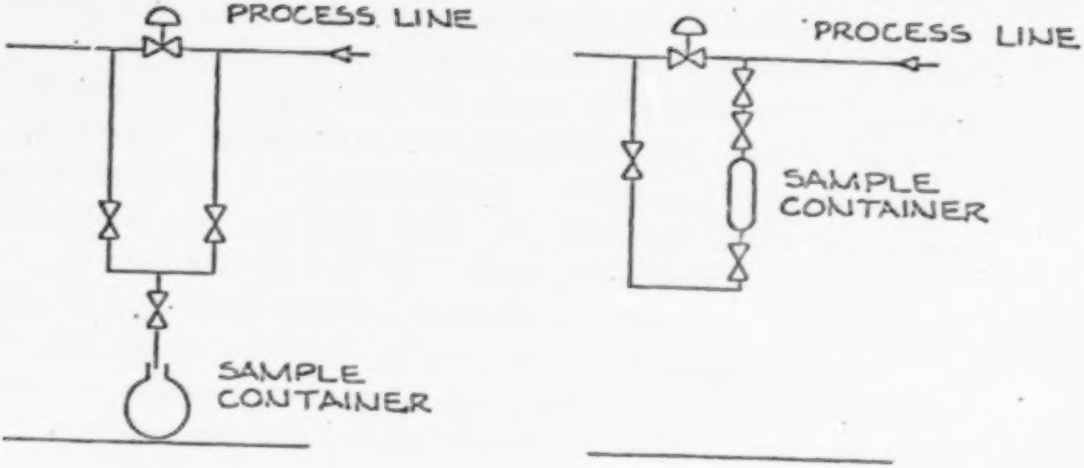
PROCESS LINE
SAMPLE CONTAINER
PROCESS LINE
SAMPLE CONTAINER

Figure 4-7. Diagram of Two Closed-Loop Sampling Systems[4]

Reduction of emissions from the use of closed-loop sampling is dependent on many highly variable factors, such as frequency of sampling and amount of purge required. For emission calculations, it has been assumed that closed-loop sampling systems will provide 100 percent control efficiency.

4.3.6 Accumulator Vessel Vents and Seal Oil Degassing System Vents

Benzene emissions from accumulator vessel vents and seal oil degassing system vents can be controlled by a closed-vent system. The flow rates of these gaseous emissions are of a much smaller magnitude than those of safety/relief valves however. These emissions could, therefore, be vented to a closed combustion device, such as a process heater or a boiler or to a vapor recovery device. The operating parameters of the combustion device will affect the overall control efficiency of the closed-vent/combustion device system. Combustion temperature and residence time are the critical parameters influencing benzene destruction efficiency, and theoretical kinetic calculations indicate that a combustion temperature of 760°C and a 0.5 second residence time will result in 100 percent benzene destruction efficiency.[22]

Organic compounds which, if combusted, would produce noxious or corrosive gases (e.g., chlorobenzene) may be present in some benzene-containing vapor streams. In these situations, benzene emissions from accumulator vessel vents and seal oil degassing vents should be controlled by a closed-vent/vapor recovery device system. The overall benzene control efficiency of a closed-vent/vapor recovery device system is dependent on the benzene collection efficiency of the vapor recovery device. Vapor recovery devices, such as adsorbers, absorbers, and condensers have been shown to range in benzene collection efficiency from 90 to 99 percent depending on the parameters of the gas stream in which the benzene is contained and the type of vapor recovery device utilized. Therefore, the overall efficiency of closed-vent/vapor recovery device systems can be expected to be in the 90 to 99 percent range.

4.4 PROCESS MODIFICATIONS

In some instances, benzene fugitive emissions could be eliminated by process modification. For some chemical processes, feedstocks other than benzene can be used, thus eliminating benzene from the process. The following are some examples of this kind of substitution:

- Maleic anhydride can be produced by oxidation of n-butane rather than by oxidation of benzene.[23,24]
- Cyclohexane can be extracted from refinery products rather than by hydrogenation of benzene.[25]

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5.0 MODIFICATION AND RECONSTRUCTION

The Environmental Protection Agency plans to propose and promulgate general provisions for Title 40 of the Code of Federal Regulation (CFR) Part 61 that will be similar to the general provisions of 40 CFR Part 60. Provisions similar to 40 CFR 60.14 and 60.15 may be included to establish that an "existing source" can become a "new source" if it is deemed modified or reconstructed. An "existing source," as defined in 40 CFR 60.2(aa), is a facility of the type for which standards have been promulgated and the construction or modification of which was begun prior to the proposal date of the applicable standards.

The following discussion examines the applicability of modification/reconstruction provisions to refining and organic chemical industry operations that involve benzene fugitive emissions.

5.1 GENERAL DISCUSSION OF MODIFICATION AND RECONSTRUCTION PROVISIONS

5.1.1 Modification

"Modification" is defined in 40 CFR Part 61, Section 61.02(j), as any physical or operational change of a stationary source which increases the emission rate of any hazardous air pollutant or which results in the emission of any hazardous air pollutant not previously emitted.

Paragraph (j)(1) and (2) list exceptions to the above definition of physical and operational changes which are not considered modifications. These changes include: (1) routine maintenance, repair, and replacement; (2) an increase in the production rate not exceeding the operating design capacity of the source; and (3) an increase in the hours of operation.

5.1.2 Reconstruction

Under provisions that may be added to 40 CRF Part 61, an existing source would become a new source upon reconstruction, irrespective of any change in emission rate. Generally, reconstruction is considered to occur upon the replacement of components if the fixed capital cost of the new components exceeds 50 percent of the fixed capital cost that would be required to construct a comparable entirely new source, and it is economically and technically feasible for the source to comply with the applicable standards. The final judgment on whether a replacement constitutes reconstruction and when it is technologically and economically feasible to comply with the applicable standards would be made by the Administrator. The Administrator's final determinations may be made on the following bases: (1) comparison of the fixed capital costs of the replacement components and a comparable entirely new source; (2) the estimated life of the source after the replacements compared to the life of a comparable entirely new source; (3) the extent to which the components being replaced cause or contribute to the emissions from the source; and (4) any economic or technical limitations on compliance with applicable standards which are inherent in the proposed replacements.

The purpose of this provision will be to ensure that an owner or operator does not perpetuate an existing source by replacing all but vestigial components, support structures, frames, housing, etc., rather than totally replacing it in order to avoid being subject to applicable new source standards.

5.2 APPLICABILITY OF MODIFICATION AND RECONSTRUCTION PROVISIONS

5.2.1 Modification

The replacement of a potential benzene fugitive emission source such as a pump or valve commonly occurs in refineries and organic chemical plants. These replacements may occur either to increase the capacity of existing process units, or to convert production from one chemical to another chemical, or to replace worn-out or obsolete equipment. If a component is replaced with an equivalent component, the benzene fugitive emissions from the source should not increase because the number of potential sources at the same benzene concentration (handling the same process stream) remains unchanged. If an existing component is replaced with a component with a higher leak rate (i.e., a mechanical seal replaced with a packed seal), however, benzene fugitive emissions would increase.

In some cases a production unit in the organic chemical industry can be converted from the production of one chemical to the production of a second chemical. If either the number of fugitive emission sources or the percentage of benzene in the process streams of the second chemical increases during this conversion, the level of benzene emissions from the unit could be expected to increase. However, controls could be added in order to reduce or maintain the same emission rates that existed prior to the conversion.

In many cases, there may be a desire to increase the capacity of an existing plant. This may be achieved by replacing certain process equipment (pumps, heat exchangers, reactors, etc.) with similar equipment but of larger capacity. If this replacement does not increase the number of fugitive emission sources handling benzene, the level of benzene fugitive emissions would not be expected to increase. However, if the number of sources were increased due to this replacement, then benzene emissions would increase.

5.2.2 Reconstruction

The replacement of equipment within production units occurs on a routine basis. In certain cases, these replacements can require the expenditure of capital that exceeds 50 percent of the fixed capital cost of the production unit. For example, replacement of existing pumps with more efficient, new pumps may exceed 50 percent of the fixed capital cost of a production unit.

6.0 MODEL UNITS AND REGULATORY ALTERNATIVES

6.1 INTRODUCTION

This chapter defines model units and alternative methods for regulating benzene fugitive emissions from these units. The model units characterize a range of existing processes that are used to produce benzene as a finished product, that use benzene in the production of other organic chemicals, or that use or produce benzene or benzene-containing streams in the manufacture of organic chemicals. Although these model unit parameters may vary from the actual parameters that exist at a particular facility, they are the most useful means of determining and comparing the environmental and economic impacts of regulatory alternatives.

Regulatory alternatives are also defined in this chapter. These regulatory alternatives represent comprehensive programs for reducing benzene fugitive emissions and provide varying degrees of emission reduction. The regulatory alternatives will be applied in the analysis of both new and existing model units.

6.2 MODEL UNIT PARAMETERS

Production units in the refining and organic chemical industries vary considerably in size, configuration, age, and complexity. Because of variations among production units, model unit parameters were selected to represent processes with varying numbers of potential leak sources. These model units are not necessarily related to production capacity, but approximate various levels of process complexity. The technical parameters of the three model units selected are shown in Table 6-1.

The model unit parameters displayed in the table were developed through analyses of process flow diagrams, material balances, and modular equipment counts for various benzene-related production operations. Since no equipment count data are available for vacuum-producing

Table 6-1. MODEL UNIT EQUIPMENT CONTAINING GREATER THAN 10 PERCENT BENZENE

Source Type[a]	Number of Components per Model Unit		
	A[b]	B[c]	C[d]
Pumps	5	15	25
Pipeline Valves, Gas[e]	30	91	151
Pipeline Valves, Liquid[e]	56	168	280
Safety/Relief Valves, Gas	3	9	16
Open-Ended Valves, Gas	3	7	12
Open-Ended Valves, Liquid	23	72	119
Drains	5	15	25
Sample Connections	9	26	44

[a] Vacuum-producing systems and product accumulator vessel vents, described in Sections 3.2.2 and 3.2.3, are not included since no equipment count data are available for these sources.

[b] Represents an average inventory of equipment for production of benzene from toluene, ethylbenzene, styrene, cumene, cyclohexane, benzene sulfonic acid, resorcinol, maleic anhydride, or 1 ethylene production unit.

[c] Represents an average inventory of equipment for production of benzene from extraction of reformate, chlorobenzenes, linear alkylbenzenes, or 2 or 3 ethylene production units.

[d] Represents an average inventory of equipment for production of benzene from extraction of pyrolysis gasoline, nitrobenzene, hydroquinone, or 4 or 5 ethylene production units.

[e] Nine percent of all pipeline valves are automatic control valves.

systems and product accumulator vessel vents, these sources are not included in the model units. These model units represent average inventories of equipment handling process streams containing greater than 10 weight percent benzene for various operations in the refining and organic chemical industries. Model A represents an average inventory of such equipment for units involved in the production of benzene from toluene, ethylbenzene, styrene, cumene, cyclohexane, benzene sulfonic acid, resorcinol, or maleic anhydride; Model B represents units involved in the production of benzene from extraction of reformate, chlorobenzene or linear alkylbenzene; Model C represents production of benzene from extraction of pyrolysis gasoline, nitrobenzene or hydroquinone. Ethylene production may be represented by either Model A, B, or C, depending on the number of ethylene production units at the plant site. One ethylene unit would be represented by Model A, two or three ethylene units would be represented by Model B, and four or five ethylene units would be represented by Model C. New units would be characterized by the same set of model units.

It is estimated that 62 percent of existing benzene-related production units in the refining and organic chemical industries would be represented by Model A, 31 percent by Model B, and 7 percent by Model C. It is expected that new units would follow the same distribution.

6.3 REGULATORY ALTERNATIVES

The regulatory alternatives in this section represent feasible methods of controlling benzene fugitive emissions from refining and organic chemical process units. Each regulatory alternative presents a comprehensive program for reduction of emissions from the sources listed in Table 6-2 by combining the individual control techniques described in Chapter 4. Table 6-2 summarizes the requirements of the regulatory alternatives.

6.3.1 Regulatory Alternative I

Regulatory Alternative I represents a baseline regulatory alternative. The baseline regulatory alternative describes the industry in the absence of additional regulatory requirements, and it provides the basis for incremental comparison of the impacts of the other regulatory alternatives.

Table 6-2. MONITORING INTERVALS AND EQUIPMENT SPECIFICATIONS FOR BENZENE FUGITIVE REGULATORY ALTERNATIVES

Source[c,d]	Regulatory Alternatives[a]							
	II[b]		III		IV		V	
	Inspection Interval	Equipment Specification	Inspection Interval	Equipment Specification	Inspection Interval	Equipment Specification	Inspection Interval	Equipment Specification
1. Pumps	Yearly[e]	None	Monthly[e]	None	None[e]	**Dual Seals**[f] and controlled degassing vent	None	**Dual Seals**[f] and controlled degassing vent
2. Pipeline Valves								
a. Gas Service	Quarterly	None	Monthly	None	Monthly	None	None	Diaphragm or sealed bellows valves
b. Liquid Service	Yearly	None	Monthly	None	Monthly	None	None	Diaphragm or sealed bellows valves
3. Safety/Relief Valves (Gas Service)	Quarterly	None	None	Rupture disks or tie into existing flare	None	Rupture disks or tie into existing flare	None	Rupture disks or tie into existing flare
4. Open-Ended Valves								
a. Gas Service	Quarterly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	None	Diaphragm or sealed bellows valve plus caps, blinds, or plugs
b. Liquid Service	Yearly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	None	Diaphragm or sealed bellows valve plus caps, blinds, or plugs
5. Drains	Yearly	None	Monthly	None	Monthly	None	None	Enclosed active drain systems
6. Sampling Connections	None	None	None	Closed-loop sampling	None	Closed-loop sampling	None	Closed-loop sampling
7. Compressors	Quarterly	None	Monthly	None	None	**Mechanical Seals**	None	**Mechanical Seals**
8. Product Accumulator Vessel Vents	None	None	None	Tie into closed control system	None	Tie into closed control system	None	Tie into closed control system

Table 6-2. MONITORING INTERVALS AND EQUIPMENT SPECIFICATIONS FOR BENZENE FUGITIVE REGULATORY ALTERNATIVES

NOTES:

[a] Regulatory Alternative I (baseline) includes no new regulatory specifications and, hence, is not included in this table. Regulatory Alternative VI is not included since it would require that no benzene be emitted from sources in the refining and organic chemical industries.

[b] Alternative II is equivalent to controls recommended in the refinery CTG for fugitive VOC emissions.

[c] Liquid service safety/relief valves, flanges, wastewater separators, vacuum-producing systems, process unit turnarounds, and cooling towers are not routinely monitored. Wastewater separators, vacuum-producing systems, process unit turnarounds, and cooling towers are not included in this table since there are no available control technologies for these sources.

[d] For all alternatives, the sources would handle organic streams with over 10 percent benzene by weight.

[e] For pumps, instrument monitoring would be supplemented with weekly visual inspections for liquid leakage. If liquid is noted to be leaking from the pump seal, the pump seal will be repaired.

[f] A sensing device should be installed between the dual seals and should be monitored to detect seal failure.

[g] Inspection applies to the valves.

As discussed in Chapter 4, a number of factors influence the baseline emission level. Examination of benzene control programs at individual plants reveals a range of existing control levels. Many plants rely on normal maintenance procedures to control fugitive emissions from leaks. Other plants may have developed a leak detection and repair program in response to OSHA regulation requirements, State or local agency regulations, or emission offset provisions. To characterize baseline conditions, however, a general description of the entire industry is desirable, rather than a description of site-specific or geographic-specific conditions. Baseline conditions, therefore, will be assumed to reflect normal existing plant maintenance procedures. These conditions are reflected in the "as is" emission factors from Table 3-1, which are used in the environmental impact analysis of the baseline regulatory alternative in Chapter 7.

6.3.2 Regulatory Alternative II

A higher level of benzene fugitive emission control could be achieved with Regulatory Alternative II than with the baseline level. This Regulatory Alternative would require periodic leak detection and repair for most sources, and the installation of specified equipment for other sources. The requirements of this regulatory alternative are based upon the recommendations of the refinery VOC leak control techniques guideline (CTG) document.[1]

Quarterly monitoring for leaks would be required for safety/relief valves, pipeline and open-ended valves in gas service, and compressors. Annual monitoring for leaks would be required for pumps, drains and valves. Weekly visual inspections of pump seals would be required; visual detection of a liquid leak would require that monitoring be initiated to determine if the action level were being exceeded, and that the pump seal be subsequently repaired, if necessary. Safety/relief valve monitoring would also be required after over-pressure relieving to detect improper reseating. Finally, open-ended valves would be required to be sealed with a cap, blind, plug, or another valve.

6.3.3 Regulatory Alternative III

Regulatory Alternative III would provide for more restrictive control than Regulatory Alternative II by increasing the frequency of leak detection and repair for some sources and requiring the installation of specified control equipment for other sources. Installation of closed-loop sampling systems would be required; rupture disks would be required on gas service safety/relief valves that vent to atmosphere; degassing vents on pump seal oil reservoirs would be required to be vented to a closed system; accumulator vessels would be required to be vented to a closed system; and open-ended valves would be required to be sealed with a cap, blind, plug, or another valve. Based on a preliminary cost analysis,[2] each of these equipment specifications is expected to have similar costs for the amount of benzene emissions reduced.

Monthly monitoring for detection of leaks from pumps, drains, compressors, and valves would also be required in this regulatory alternative. The purpose of the increased frequency of monitoring is to reduce emissions from residual leaking sources (i.e., those sources that are found leaking and are repaired and recur before the next inspection, and those sources that begin leaking between inspections). Weekly visual inspections of pump seals would be required as discussed for Regulatory Alternative II.

6.3.4 Regulatory Alternative IV

Regulatory Alternative IV includes equipment specifications that are expected to have greater costs for the amount of benzene emissions reduced than for those included in Regulatory Alternative III. Mechanical seal systems would be required on pumps and compressors in this regulatory alternative in addition to the equipment requirements for the sampling systems, gas service safety/relief valves, degassing vents, accumulator vessel vents, and open-ended valves specified in Regulatory Alternative III. Diaphragm and sealed-bellows valves are not included because the expected cost for the amount of benzene emissions reduced, based on a preliminary cost analysis, was much greater than that for double seals.[2] In addition to these equipment specifications, drains and valves would be required to be monitored for leaks each month, as in Regulatory Alternative III.

6.3.5 Regulatory Alternative V

This regulatory alternative would require leakless emission control equipment for the sources listed in Table 6-2. In addition to the equipment specifications discussed for Regulatory Alternative IV, this regulatory alternative would require installation of diaphragm or sealed-bellows type valves, and would require drains to be enclosed. All of these sources would, therefore, be controlled to the maximum degree, and leaks would virtually be eliminated from these sources.

6.3.6 Regulatory Alternative VI

This regulatory alternative would require the elimination of all benzene fugitive emissions from the affected industry. Although the equipment specifications required in Regulatory Alternative V would virtually eliminate such emissions from equipment handling greater than 10 weight percent benzene, there would still be some emissions from equipment handling less than 10 weight percent benzene.

Three approaches to totally eliminating benzene fugitive emissions were considered. These are: (1) to require the use of leakless technology for all equipment handling benzene-containing streams, (2) to require the use of substitute feedstocks, thus eliminating the use of benzene, and (3) to prohibit the production or consumption of benzene.

The use of leakless technology could eliminate most benzene fugitive emissions. However, there would still be some benzene emissions from spills and occasional equipment failure.

The use of substitute feedstocks could be effective for some operations; for example, n-butane could be used in the production of maleic anhydride instead of using benzene. This approach could not be used for all benzene-consuming processes, however, since there are no substitutes for benzene in some cases.

The only approach that could totally eliminate benzene fugitive emissions is the prohibition of all benzene-producing and consuming processes. This approach, however, would lead to the shutdown of all refineries and a number of chemical plants because of the presence of benzene in refinery feedstocks and the lack of available substitutes for benzene in many chemical plant operations.

6.4 REFERENCES

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7.0 ENVIRONMENTAL IMPACT

7.1 INTRODUCTION

The environmental impacts for the regulatory alternatives presented in Chapter 6 are discussed in this chapter. Both beneficial and adverse impacts are assessed for air and water pollution, solid waste, and energy use. Included are the derivations of controlled benzene emission factors for the designated sources. Total benzene emissions, incremental benzene emission reductions for the regulatory alternatives, and projected future benzene emissions are presented. Other environmental concerns are discussed, including irreversible and irretrievable commitment of resources as well as the environmental impact of delayed regulatory action.

7.2 AIR QUALITY IMPACTS

7.2.1 Development of Benzene Emission Levels

In order to estimate the impacts of the regulatory alternatives on benzene emission levels, emission factors for the model units are determined for each regulatory alternative. Controlled VOC emission factors for Alternatives II, III, IV, and V are presented in Tables 7-1 through 7-4.

Alternative I represents baseline emissions and includes no new regulatory specifications. Regulatory Alternative VI represents no allowable benzene fugitive emissions from sources in the refining and organic chemical industries. As discussed in Chapter 6, neither of these alternatives is being considered as a viable control option.

The factors used to estimate the emissions from sources controlled by a leak detection and repair program are calculated for each source using the methodology presented in Chapter 4. The controlled emission factors are calculated by multiplying the uncontrolled factors for each source by a set of correction factors, which account for imperfect

Table 7-1. CONTROLLED VOC EMISSION FACTORS FOR REGULATORY ALTERNATIVE II

Source	Inspection Interval[a]	Uncontrolled Emission Factor[b] (Kg/hr)	Correction Factors				Control Efficiency (AxBxCxD)	Controlled Emission Factor[g] (Kg/hr)
			A[c]	B[d]	C[e]	D[f]		
Pumps	Yearly	0.12[h]	0.87	0.80	0.98	0.92	0.63	0.044
Valves[i]								
Gas	Quarterly	0.021	0.98	0.90	0.98	0.99	0.86	0.003
Liquid	Yearly	0.010[h]	0.84	0.80	0.98	0.94	0.62	0.004
Gas Service Safety/Relief Devices	Quarterly	0.16	0.69	0.90	0.98	0.98	0.60	0.064
Drains	Yearly	0.032	0.46	0.80	0.98	0.91	0.33	0.021
Compressors	Quarterly	0.44	0.84	0.90	0.98	0.97	0.72	0.123

[a] From Table 6-2.

[b] From Table 3-1.

[c] Theoretical maximum control efficiency — From Table 4-2.[1]

[d] Leak occurrence and recurrence correction factor — Assumed to be 0.80 for yearly inspection, 0.90 for quarterly inspection, and 0.95 for monthly inspection.[2]

[e] Non-instantaneous repair correction factor — for a 15-day maximum allowable repair time,[2] the 7.5-day average repair time yields a 0.98 yearly correction factor: [365 - (15/2)] ÷ 365 = 0.98.[2]

[f] Imperfect repair correction factor — From Table 4-3, calculated as 1 - (f + F), where f = average emission rate for sources at 1000 ppm and F = average emission rate for sources greater than 10,000 ppm.[1,2]

[g] Controlled emission factor = uncontrolled emission factor x [1 - (A X B X C X D)].

[h] Emission factor for light liquid streams is used. (Reference 1)

[i] Emission factors for in-line and open-ended valves are identical, since emissions from the open end would be essentially eliminated by a cap, plug, blind or second valve.

Table 7-2. CONTROLLED VOC EMISSION FACTORS FOR REGULATORY ALTERNATIVE III

Source	Inspection Interval[a]	Uncontrolled Emission Factor[b] (Kg/hr)	Correction Factors				Control Efficiency (AxBxCxD)	Controlled Emission Factor[g] (Kg/hr)
			A[c]	B[d]	C[e]	D[f]		
Pumps	Monthly[h]	0.12[j]	0.87	0.95	0.98	0.92	0.75	0.030
Valves[k]								
Gas	Monthly	0.021	0.98	0.95	0.98	0.99	0.90	0.002
Liquid	Monthly	0.010[j]	0.84	0.95	0.98	0.94	0.74	0.003
Gas Service Safety/Relief Devices	None[i]	0.16	NA	NA	NA	NA	--	0.0
Drains	Monthly	0.032	0.46	0.95	0.98	0.91	0.39	0.020
Compressors	Monthly	0.44	0.84	0.95	0.98	0.97	0.76	0.106

[a] From Table 6-2.

[b] From Table 3-1.

[c] Theoretical maximum control efficiency — From Table 4-2.[1]

[d] Leak occurrence and recurrence correction factor — Assumed to be 0.80 for yearly inspection, 0.90 for quarterly inspection, and 0.95 for monthly inspection.[2]

[e] Non-instantaneous repair correction factor — for a 15-day maximum allowable repair time, the 7.5-day average repair time yields a 0.98 yearly correction factor: $[365 - (15/2)] \div 365 = 0.98$.[2]

[f] Imperfect repair correction factor — From Table 4-3, calculated as $1 - (f + F)$, where f = average emission rate for sources at 1000 ppm and F = average emission rate for sources greater than 10,000 ppm.[1,2]

[g] Controlled emission factor = uncontrolled emission factor x $[1 - (A \times B \times C \times D)]$.

[h] For pumps, instrument monitoring should be supplemented with weekly visual inspections for liquid leakage.

[i] Control equipment for this source is specified in Table 6-2, and about 100 percent control efficiency is assumed. Therefore, the correction factors are not applicable, and there are essentially no fugitive emissions from the source.

[j] Emission factor for light liquid streams is used. (Reference 1)

[k] Emission factors for in-line and open-ended valves are identical, since emissions from the open end would be essentially eliminated by a cap, blind, plug or second valve.

Table 7-3. CONTROLLED VOC EMISSION FACTORS FOR REGULATORY ALTERNATIVE IV

Source	Inspection Interval[a]	Uncontrolled Emission Factor[b] (Kg/hr)	Correction Factors				Control Efficiency (AxBxCxD)	Controlled Emission Factor[g] (Kg/hr)
			A[c]	B[d]	C[e]	D[f]		
Pumps	None[h]	0.12[i]	NA	NA	NA	NA	--	0.0
Valves[j] Gas	Monthly	0.021	0.98	0.95	0.98	0.99	0.90	0.002
Liquid	Monthly	0.010[i]	0.84	0.95	0.98	0.94	0.74	0.003
Gas Service Safety/Relief Devices	None[h]	0.16	NA	NA	NA	NA	--	0.0
Drains	Monthly	0.032	0.46	0.95	0.98	0.91	0.39	0.020
Compressors	None[h]	0.44	NA	NA	NA	NA	--	0.0

[a] From Table 6-2.

[b] From Table 3-1.

[c] Theoretical maximum control efficiency — From Table 4-2.[1]

[d] Leak occurrence and recurrence correction factor — Assumed to be 0.80 for yearly inspection, 0.90 for quarterly inspection, and 0.95 for monthly inspection.[2]

[e] Non-instantaneous repair correction factor — for a 15-day maximum allowable repair time, the 7.5-day average repair time yields a 0.98 yearly correction factor: $[365 - (15/2)] \div 365 = 0.98$.[2]

[f] Imperfect repair correction factor — From Table 4-3, calculated as $1 - (f \div F)$, where f = average emission rate for sources at 1000 ppm and F = average emission rate for sources greater than 10,000 ppm.[1,2]

[g] Controlled emission factor = uncontrolled emission factor x $[1 - (A \times B \times C \times D)]$.

[h] Control equipment for this source is specified in Table 6-2, and about 100 percent control efficiency is assumed. Therefore, the correction factors are not applicable, and there are essentially no fugitive emissions from the source.

[i] Emission factor for light liquid streams is used. (Reference 1)

[j] Emission factors for in-line and open-ended valves are identical, since emissions from the open end would be essentially eliminated by a cap, blind, plug or second valve.

Table 7-4. CONTROLLED VOC EMISSION FACTORS FOR REGULATORY ALTERNATIVE V

Source	Inspection Interval[a]	Uncontrolled Emission Factor[b] (Kg/hr)	Correction Factors				Control Efficiency (AxBxCxD)	Controlled Emission Factor[g] (Kg/hr)
			A[c]	B[d]	C[e]	D[f]		
Pumps	None[h]	0.12[i]	NA	NA	NA	NA	--	0.0
Valves[j]								
Gas	None[h]	0.021	NA	NA	NA	NA	--	0.0
Liquid	None[h]	0.010[i]	NA	NA	NA	NA	--	0.0
Gas Service Safety/Relief Devices	None[h]	0.16	NA	NA	NA	NA	--	0.0
Drains	None[h]	0.032	NA	NA	NA	NA	--	0.0
Compressors	None[h]	0.44	NA	NA	NA	NA	--	0.0

[a] From Table 6-2.

[b] From Table 3-1.

[c] Theoretical maximum control efficiency — From Table 4-2.[1]

[d] Leak occurrence and recurrence correction factor — Assumed to be 0.80 for yearly inspection, 0.90 for quarterly inspection, and 0.95 for monthly inspection.[2]

[e] Non-instantaneous repair correction factor — for a 15-day maximum allowable repair time, the 7.5-day average repair time yields a 0.98 yearly correction factor: [365 - (15/2)] ÷ 365 = 0.98.[2]

[f] Imperfect repair correction factor — From Table 4-3, calculated as 1 - (f ÷ F), where f = average emission rate for sources at 1000 ppm and F = average emission rate for sources greater than 10,000 ppm.[1,2]

[g] Controlled emission factor = uncontrolled emission factor x [1 - (A X B X C X D)].

[h] Control equipment for this source is specified in Table 6-2, and about 100 percent control efficiency is assumed. Therefore, the correction factors are not applicable, and there are essentially no fugitive emissions from the source.

[i] Emission factor for light liquid streams is used. (Reference 1)

[j] Emission factors for in-line and open-ended valves are identical, since emissions from the open end would be essentially eliminated by a cap, plug, blind or second valve.

repair, non-instantaneous repair, and the occurrence or recurrence of leaks between inspections.

For each regulatory alternative and model unit, the number of components handling greater than 10 percent benzene (Table 6-1) is multiplied by the controlled VOC emission factor for each source (Tables 7-1 through 7-4). Summing the VOC emissions from these sources yields a total VOC emission estimate for equipment in each model unit handling greater than 10 percent benzene. Since all sources do not handle pure benzene, it is necessary to convert the VOC emission estimates to benzene emission estimates. This is accomplished by first estimating an average percent benzene for equipment in each process containing greater than 10 percent benzene by examining flow diagrams and material balances. Table 7-5 shows the resulting average percent benzene for each process. Knowing the existing distribution of processes within each model unit category (also shown in Table 7-5), it is then possible to calculate a weighted average percent benzene for equipment containing greater than 10 percent benzene in each model unit. From the table, these weighted averages are calculated to be 63, 55, and 75 percent for model units A, B, and C, respectively. Application of these factors to the VOC emissions yields a benzene emission estimate for equipment containing greater than 10 percent benzene in each model unit and for each regulatory alternative. An example calculation is given below for pumps containing greater than 10 percent benzene in Model Unit A under Regulatory Alternative II.

$$\begin{array}{l}\text{Benzene emissions from}\\ \text{>10 percent benzene (Bz)}\\ \text{Pumps in Model Unit A}\\ \text{Under Regulatory}\\ \text{Alternative II (kg/hr)}\end{array} = 5\left(\begin{array}{l}\text{>10 percent Bz Pumps}\\ \text{in Model Unit A}\\ \text{(from Table 6-1)}\end{array}\right) \times 0.044\left(\begin{array}{l}\text{Kg VOC per hour}\\ \text{per pump for}\\ \text{Regulatory}\\ \text{Alternative II}\\ \text{(from Table 7-1)}\end{array}\right)$$

$$\times \quad 0.63\left(\begin{array}{l}\text{Weighted factor}\\ \text{of percent benzene}\\ \text{in Model Unit A}\\ \text{(from Table 7-5)}\end{array}\right) = \begin{array}{l}\text{0.14 kg Benzene per hour from}\\ \text{>10 percent Bz Pumps in Model}\\ \text{Unit A, Regulatory Alternative II}\end{array}$$

Table 7-5. CALCULATION OF WEIGHTED PERCENT BENZENE FOR EMISSION SOURCES IN MODEL UNITS[a]

	Number of Units[b] (1980)[b]	Percent of Total Model Units	Average Percent Benzene for Equipment in Each Process[a,c]	Weighted Percent Benzene
MODEL UNIT A				
Ethylene (1 Unit)	41	28.3	33	9
Ethylbenzene	22	15.2	71	11
Benzene (Dealkylation)	20	13.8	75	10
Styrene	19	13.1	30	4
Cumene	16	11.0	100	11
Cyclohexane	12	8.3	100	8
Maleic Anhydride	10	6.9	100	7
Benzenesulfonic Acid	5	3.4	85	3
TOTAL	145	100.0	---	63
MODEL UNIT B				
Benzene (Reformer)	49	68.0	45	31
Chlorobenzene	12	16.7	100	17
Ethylene (2 or 3 Units)	7	9.7	33	3
Alkylbenzenes	4	5.6	65	4
TOTAL	72	100.0	---	55
MODEL UNIT C				
Benzene (Pyrolysis Gas)	12	50.0	57	29
Nitrobenzene	10	41.6	100	42
Hydroquinone	1	4.2	75	3
Ethylene (4 or 5 Units)	1	4.2	33	1
TOTAL	24	100.0	---	75

Table 7-5. CALCULATION OF WEIGHTED PERCENT BENZENE FOR EMISSION SOURCES IN MODEL UNITS[a] (Concluded)

NOTES

[a] The Resorcinol process is not included in this analysis. Resorcinol is produced at only one facility in the country, and the process would have only one feed pump and one control valve in benzene service. Although this equipment would be covered by the regulation, this process is much smaller than the smallest model unit and, hence, would not significantly impact the analysis. Calculations for all of the other processes are for designated sources handling greater than ten percent benzene.

[b] Includes plants under construction expected to be completed in 1980.

[c] The average percentage of benzene for designated sources in each product process containing greater than 10 percent benzene is derived from observations of flow diagrams, material balances, and equipment counts for each manufacturing process. For each of the products listed, the percentage of benzene represents a weighted average of the number of pieces of equipment and the concentrations of benzene in each product stream:

$$\text{Weighted Percent Benzene} = \frac{\sum\left(\text{Number of Pieces of Equipment} \times \text{Concentration in Each Stream}\right)}{\text{Total Pieces of Equipment}}$$

Example: If there are 5 pumps at 100 percent benzene and 5 pumps at 50 percent benzene, then the weighted average of percent benzene for the equipment can be expressed as

$$\text{Weighted Percent Benzene} = \frac{(5 \times 100) + (5 \times 50)}{10} = \underline{\underline{75 \text{ Percent}}}$$

Using a similar technique, it is also possible to estimate benzene emissions from equipment handling streams with less than 10 percent benzene.[3] VOC emissions from these sources are calculated using the same VOC emission factors as are used for equipment handling over 10 percent benzene. The average percent benzene for sources containing less than 10 percent benzene is estimated by examining flow diagrams and material balances. For each process, benzene emissions from these sources are then calculated. A weighted average of the processes is then applied to give the "residual" benzene emissions from the equipment handling less than 10 percent benzene for each model unit. These emissions are calculated to be 0.35, 0.55, and 0.48 kilograms per hour for Model Units A, B, and C, respectively. It should be noted that these emissions would not be affected by this regulation and, therefore, are included in the benzene emission totals for each of the regulatory alternatives.

Tables 7-6 through 7-8 present benzene emission estimates by source for each of the model units and regulatory alternatives. In general for each model unit, valves and pumps containing greater than 10 percent benzene contribute about half of the total benzene emissions from all sources. Table 7-9 presents total national benzene emissions (megagrams per year) for each alternative based on the number of model units expected to be in operation in 1980 and the benzene emission totals per model unit and regulatory alternative from Tables 7-6 through 7-8.

7.2.2 Future Benzene Emissions

In order to assess potential future impacts of the regulatory alternatives, benzene emissions are projected over a ten-year period (1981-1990). To estimate future benzene emissions, two assumptions are made:

1. The average process unit production rate as a percentage of unit capacity for all benzene products remains the same over the projected ten-year period.
2. An increase in demand is accounted for by building new units, expanding the capacity of existing units, or by renovating existing units.

Table 7-6. BENZENE EMISSIONS (kg/hr) BY SOURCE FOR THE REGULATORY ALTERNATIVES - MODEL UNIT A

	Regulatory Alternative[a]				
Source	I	II	III	IV	V
Pumps	0.38	0.14	0.10	0.00[c]	0.00[c]
Valves					
Gas	0.40	0.06	0.04	0.04	0.00[c]
Liquid	0.36	0.14	0.11	0.11	0.00[c]
Safety/Relief Valves (Gas)	0.30	0.12	0.00[c]	0.00[c]	0.00[c]
Open-ended Valves					
Gas	0.05	0.01	0.00[d]	0.00[d]	0.00[c]
Liquid	0.19	0.06	0.04	0.04	0.00[c]
Drains	0.10	0.07	0.06	0.06	0.00[c]
Sampling Connections	0.09	0.09	0.00[c]	0.00[c]	0.00[c]
Other Equipment[b]	0.35	0.35	0.35	0.35	0.35
Total Emissions (kg/hr)	2.22	1.04	0.70	0.60	0.35

[a] The regulatory alternatives are summarized in Table 6-2. Alternative I represents baseline emissions.

[b] Other equipment includes sources containing less than 10 percent benzene.

[c] Control equipment for this source is specified in Table 6-2, and about 100 percent control efficiency is assumed. Therefore, there are essentially no fugitive emissions from the source.

[d] Negligible emissions - less than 0.005 kg/hr.

Table 7-7. BENZENE EMISSIONS (kg/hr) BY SOURCE FOR THE REGULATORY ALTERNATIVES - MODEL UNIT B

	Regulatory Alternative[a]				
Source	I	II	III	IV	V
Pumps	0.97	0.36	0.24	0.00[c]	0.00[c]
Valves					
Gas	1.03	0.15	0.10	0.10	0.00[c]
Liquid	0.91	0.37	0.27	0.27	0.00[c]
Safety/Relief Valves (Gas)	0.78	0.32	0.00[c]	0.00[c]	0.00[c]
Open-Ended Valves					
Gas	0.09	0.01	0.01	0.01	0.00[c]
Liquid	0.52	0.16	0.12	0.12	0.00[c]
Drains	0.26	0.17	0.15	0.15	0.00[c]
Sampling Connections	0.21	0.21	0.00[c]	0.00[c]	0.00[c]
Other Equipment[b]	0.55	0.55	0.55	0.55	0.55
Total Emissions (kg/hr)	5.32	2.30	1.44	1.20	0.55

[a] The regulatory alternatives are summarized in Table 6-2. Alternative I represents baseline emissions.

[b] Other equipment includes sources containing less than 10 percent benzene.

[c] Control equipment for this source is specified in Table 6-2, and about 100 percent control efficiency is assumed. Therefore, there are essentially no fugitive emissions from the source.

Table 7-8. BENZENE EMISSIONS (kg/hr) BY SOURCE FOR THE REGULATORY ALTERNATIVES - MODEL UNIT C

Source	Regulatory Alternative[a]				
	I	II	III	IV	V
Pumps	2.24	0.82	0.56	0.00[c]	0.00[c]
Valves					
Gas	2.36	0.34	0.23	0.23	0.00[c]
Liquid	2.09	0.85	0.62	0.62	0.00[c]
Safety/Relief Valves (Gas)	1.91	0.79	0.00[c]	0.00[c]	0.00[c]
Open-ended Valves					
Gas	0.22	0.03	0.02	0.02	0.00[c]
Liquid	1.17	0.36	0.26	0.26	0.00[c]
Drains	0.60	0.39	0.35	0.35	0.00[c]
Sampling Connections	0.49	0.49	0.00[c]	0.00[c]	0.00[c]
Other Equipment[b]	0.48	0.48	0.48	0.48	0.48
Total Emissions (kg/hr)	11.56	4.55	2.52	1.96	0.48

[a] The regulatory alternatives are summarized in Table 6-2. Alternative I represents baseline emissions.

[b] Other equipment includes benzene sources containing less than 10 percent benzene.

[c] Control equipment for this source is specified in Table 6-2, and about 100 percent control efficiency is assumed. Therefore, there are essentially no fugitive emissions from the source.

Table 7-9. TOTAL NATIONAL BENZENE EMISSIONS FROM REFINING AND ORGANIC CHEMICAL PROCESSES IN 1980[a]

Regulatory Alternative	Emissions (Mg/yr)[b]	Emission Reduction From Alternative I	
		Mg/yr	Percent
I[c]	8250	----	----
II	3570	4680	57
III	2230	6020	73
IV	1860	6390	77
V	860[d]	7390	90

[a] Any process that has equipment handling over 10 percent benzene streams is included in this analysis. The emission totals include the emissions from equipment over 10 percent and under 10 percent benzene for each of these processes. Benzene emissions per year are calculated from an assumed process operation of 8400 hours per year.

[b] Calculated for each regulatory alternative as the summation of the product of the annual emissions (Mg/yr) from each model unit and the number of existing refinery and chemical units that are represented by that model unit. The number of existing units operating in 1980 is as follows:

Model Unit A — 145
Model Unit B — 72
Model Unit C — 24

[c] Represents baseline emissions (the industry in the absence of new regulations).

[d] Residual from equipment handling less than 10 percent benzene.

In order to calculate benzene emission levels over the 10-year period, a weighted growth rate for each model unit is calculated based on the number of existing units in the base year of the analysis (1980), and the average annual growth rate for each production process. For each model unit, Table 7-10 lists the number of plants estimated in operation in 1980 and the average annual growth rates for each product. The weighted average annual growth rates for each model unit are approximately 6, 2, and 10 percent for Model Units A, B, and C, respectively.

In the determination of future impacts of benzene fugitive emissions from refineries and chemical plants, a distinction is made between new unit growth and growth as a result of unit replacement. For each model unit, the weighted average annual growth rate calculated in Table 7-10 represents a net increase attributable to overall industrial growth. The number of units constructed in any year equals this net increase plus the number of units constructed to replace ones that cease production due to obsolescence, deterioration, or other factors.

For each model unit, the number of new units (N) constructed in any period (X years) is calculated from the number of existing units (E) in 1980 and the projected average annual growth rate (i) for the model unit, using a rearrangement of the formula for simple interest compounded annually, as follows:

$$N = E(1 + i)^x - E$$

As an example, to calculate the projected number of new Model A units constructed between 1981 and 1985, the above formula is applied as follows:

$$N_{1981-1985} = 145\ (1 + .0576)^5 - 145$$

$$= \underline{47} \text{ new plants.}$$

Assuming an average unit life of 20 years, the number of replacements (R) is calculated by the following:

$$R = \frac{N}{rf} - N,$$

where N = the number of new units and

rf = a replacement factor as follows:

$$rf = 1 - \frac{1}{(1 + i)^{20}}.$$

Table 7-10. NUMBERS OF UNITS ESTIMATED TO MEET 1980 DEMAND FOR BENZENE AND BENZENE DERIVATIVES BY MODEL UNITS

Model A	Estimated Number of Units in "Year 0" (1980)	Percent of Total Units	Average Annual Growth Rate[4-14] (Percent)	Weighted Annual Growth Rate (Percent)*
Ethylene (1 unit)	41	28.3	5.5	1.56
Ethylbenzene	22	15.2	6.0	0.91
Benzene (Dealkylation)	20	13.8	3.7	0.51
Styrene	19	13.1	6.0	0.79
Cumene	16	11.0	7.5	0.82
Cyclohexane	12	8.3	5.0	0.41
Maleic Anhydride	10	6.9	11.0	0.76
Benzenesulfonic Acid	5	3.4	0.0	0.00
Total	145	100.0	--	5.76
Model B				
Benzene (Reformer)	49	68.0	1.5	1.03
Chlorobenzene	12	16.7	1.5	0.25
Ethylene (2 or 3 units)	7	9.7	5.5	0.53
Alkylbenzenes	4	5.6	2.0	0.11
Total	72	100.0	--	1.92
Model C				
Benzene (Pyrolysis Gas)	12	50.0	14.1	7.05
Nitrobenzene	10	41.6	6.0	2.50
Hydroquinone	1	4.2	0.0	0.00
Ethylene (4 or 5 units)	1	4.2	5.5	0.23
Total	24	100.0	--	9.78

*Does not include replacement of old units.

The results are presented in Table 7-11, which shows the projected growth of new and replacement units over a 10-year period (1981-1990).

Using the benzene emission estimates for each regulatory alternative and model unit from Tables 7-6 through 7-8, the expected benzene emissions that will be contributed by new units and replacements can be calculated by multiplying the benzene emissions by the number of new units and replacements estimated to be operating between 1981 and 1990 (Table 7-11). For each alternative, emissions from Model Units A, B, and C are summed to obtain the total benzene emissions for the regulatory alternative. Table 7-12 presents anticipated benzene fugitive emissions for new units and replacements for each alternative over the ten-year period.

7.3 WATER POLLUTION IMPACT

Implementation of any of the regulatory alternatives would result in slight positive benefits to water quality, depending on the specific control requirements of the alternative. The regulatory alternatives would not cause the organic streams being handled by affected equipment to contact water. Neither would benzene emissions be physically removed (as in the case of wet scrubber control for particulates). Rather, emissions are expected to be contained. Therefore, implementing any of the benzene fugitive emissions alternatives would not adversely impact water quality. At best, the quality of runoff water might improve slightly due to the improved containment of benzene and other volatile organic compounds.

Specifically, provisions of Regulatory Alternative II would require leak detection and repair for some liquid service equipment. Repair of this equipment would require that process liquids be drained or flushed, thus generating a small negative wastewater impact.

Alternative III would require that sample purge material be returned to the system or contained. This requirement would result in a small positive wastewater impact, since in some plants, this material is currently routed to a drain system.

Table 7-11. CUMULATIVE ANNUAL NUMBER OF PROJECTED NEW UNITS AND REPLACEMENTS BETWEEN 1981 AND 1990[a]

Year	Model Unit A	Model Unit B	Model Unit C
1981			
New[b]	8	1	2
Replacement[c]	4	0	0
1982			
New[b]	17	3	5
Replacement[c]	8	1	1
1983			
New[b]	27	4	8
Replacement[c]	13	2	1
1984			
New[b]	36	6	11
Replacement[c]	17	3	2
1985			
New[b]	47	7	14
Replacement[c]	23	4	3
1990			
New[b]	109	15	37
Replacement[c]	53	7	7

NOTES FOR TABLE 7-11

[a] Projections of new and replacement unit growth over a 10-year period were based on the following:

Model Unit	Number of Existing Plants (E) in 1980	Projected Growth Rate (i) (% per year)	Replacement Factor (rf)
A	145	5.76	0.674
B	72	1.92	0.688[d]
C	24	9.78	0.845

[b] Projected number of new plants (N) was determined from the following:

$$N = E(1 + i)^x - E$$

where E = number of existing plants in 1980
i = projected average annual growth rate
x = Δyear from 1980 (1,2,3...10)

[c] Projections of replacements were based on the replacement factor (rf):

$$rf = 1 - \frac{1}{(1+i)^{20}},$$

assuming an average unit life of 20 years. Number of replacements (r) is calculated from the following:

$$R = \frac{N}{rf} - N,$$

where N = number of new plants
and rf = replacement factor.

[d] The replacement factor of 0.688 for Model Unit B reflects a 6 percent annual growth rate over the last 20 years (1960-1980) rather than the 1.92 percent annual growth rate over the next 10 years.

Table 7-12. CUMULATIVE ANNUAL ESTIMATED BENZENE FUGITIVE EMISSIONS FROM NEW UNITS AND REPLACEMENTS BETWEEN 1981 and 1990 (Mg/year)

		Regulatory Alternative				
Year		I	II	III	IV	V
1981						
	New	388	165	101	84	36
	Replacement	74	35	23	20	12
1982						
	New	936	397	242	199	84
	Replacement	291	127	80	67	32
1983						
	New	1458	617	377	309	130
	Replacement	429	190	122	102	52
1984						
	New	2006	849	517	425	178
	Replacement	645	282	178	149	72
1985						
	New	2547	1078	658	540	227
	Replacement	898	391	247	206	98
1990						
	New	6292	2649	1606	1315	539
	Replacement	1979	862	544	455	217

Under Regulatory Alternative IV or V, a dual mechanical seal/degassing vent arrangement would reduce product leakage from pumps and thus result in a slight positive impact on water quality. Implementation of Regulatory Alternative IV could also result in a negative impact on water quality from the operation of possible control devices which "capture" fugitive VOC from the degassing vent. If a carbon adsorption device were used, for example, a wastewater stream containing suspended solids and small quantities of dissolved organics would be produced during the carbon regeneration process if the carbon is regenerated at the unit. The use of a refrigeration process as the control device would possibly result in a condensate containing dissolved organics. The wastewater flow rates would be quite small since the amount of VOC being removed is small, and this wastewater would generally be suitable for treatment in existing wastewater treatment systems.

7.4 SOLID WASTE IMPACT

The regulatory alternatives will contain benzene in the vapor and liquid states. This contained material is not expected to generate a solid waste. The solid wastes associated with the alternatives are replaced mechanical seals, packing, rupture disks, and valves. In Regulatory Alternative II, capping open-ended valves would result in no solid waste impacts. Implementation of Regulatory Alternative III, which requires the installation of rupture disks on safety/relief valves, a closed-loop sampling system, and seals on open-ended valves and lines would have a negligible impact. For Regulatory Alternative IV, dual mechanical seals would be retrofitted on pumps. Existing packing materials and single mechanical seals may not be reusable and hence would be discarded. As the dual seals wear out, they also would be replaced and the old seals would be discarded. This material would have a very minor impact on the quantity of solid waste generated by the plant, however, since existing single seals would have worn out and been replaced also. Therefore, Regulatory Alternative IV would have a negligible negative impact on solid waste. In addition to the equipment specifications of Regulatory Alternative IV, Regulatory Alternative V would require that diaphragm or sealed-bellows type valves be installed and that drains be enclosed. The solid wastes generated by the replacement of single mechanical seals and packing material, as in Regulatory Alternative IV, and the disposal of unrecyclable valves would have an insignificant impact on solid waste.

7.5 ENERGY IMPACT

The controls necessary for the implementation of Regulatory Alternatives II through V would require no significant increase in energy consumption. The application of dual seals, however, would require a minimal increase in energy usage over single seal operation because of the slight increase in seal/shaft friction and because of the energy required to operate the fluid flush system. Since the product emissions do have an energy value, a net positive energy impact is expected.

The average energy value of total VOC fugitive emissions from the refining and organic chemical industries is estimated as 8.62×10^6 joules/kg.[15] Table 7-13 presents the energy savings over a five-year period that result from the VOC fugitive emission reductions associated with Regultory Alternatives II through V. Since Regulatory Alternative V represents the most stringent option, it achieves the greatest emission reduction by reducing uncontrolled fugitive emissions by 72,700 Mg over a five-year period. These "recovered" VOC emissions have a total energy value of 627 terajoules based on a heat value of 8.62×10^6 joules/kg. Assuming an energy value of 6.12×10^9 joules per barrel of crude oil, the energy value of the recovered VOC fugitive emissions is approximately 102,400 barrels of crude oil for the period 1981 through 1985 under Regulatory Alternative V. This represents an average annual savings of 20,480 barrels of crude oil over the five-year period.

7.6 OTHER ENVIRONMENTAL CONCERNS

7.6.1 Irreversible and Irretrievable Commitment of Resources

Implementation of any of the regulatory alternatives is not expected to result in any irreversible or irretrievable commitment of resources. As previously noted, the regulatory alternatives should help to save crude oil due to the energy savings associated with the reductions in emissions. Materials used in double mechanical pump seal mechanisms, such as tungsten carbide, will be committed, but the

Table 7-13. ENERGY IMPACT OF BENZENE EMISSION REDUCTION FOR REGULATORY ALTERNATIVES

	Reduction from Baseline Emissions Under Regulatory Alternatives[a,b] (1000 Mg)				Energy Value of Emission Reductions Under Regulatory Alternatives[c] (10^9 Btu)				Crude Oil Equivalent of Emission Reductions[d] (1000 barrels - bbl)			
Year	II	III	IV	V	II	III	IV	V	II	III	IV	V
1981	7.93	10.2	10.8	12.5	68.4	87.9	93.1	108	11.2	14.4	15.2	17.6
1982	8.59	11.0	11.7	13.6	74.0	94.8	101	117	12.1	15.5	16.5	19.1
1983	9.16	11.8	12.5	14.5	79.0	102	108	125	12.9	16.7	17.6	20.4
1984	9.82	12.6	13.4	15.5	84.6	109	116	134	13.8	17.8	19.0	21.9
1985	10.5	13.5	14.3	16.6	90.5	116	123	143	14.8	19.0	20.1	23.4
5-year Total	46.0	59.1	62.7	72.7	397	510	541	627	64.8	83.4	88.4	102

[a] Alternative I represents baseline emissions.

[b] Emission reduction calculated from VOC emissions per model unit and regulatory alternative as well as the total number of units projected to be in operation between 1981 and 1985.

[c] Energy value of benzene is based on 8.62×10^6 joules (from conversion of 17,986 Btu/lb given in Ref. 15, p. 3-143).

[d] Based on 6.12×10^9 joules/barrel crude oil.

amount of the material lost will be very slight, and although the material is valuable, it is not particularly scarce. Other materials used to manufacture piping, valves, rupture disks and line caps are not scarce and will not be committed in significant quantities for any of the regulatory alternatives.

7.6.2 Environmental Impact of Delayed Regulatory Action

As indicated above, implementation of any regulatory alternative would only have minor impacts on water and solid wastes. Consequently, delaying regulatory action will have essentially no impact on these problems. However, a delay in implementing the alternatives will have a greater impact on air pollution and associated energy impacts. The air and energy impacts of delayed standards are shown in Table 7-13. The emission reductions and associated energy savings shown would be lost at the rates shown for each of the five years.

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8.0 COST OF CONTROLS

8.1 INTRODUCTION

In order to estimate the economic impact of the regulatory alternatives on the petroleum refining and organic chemical manufacturing industries, it is first necessary to calculate the control costs of the regulatory alternatives. Installed capital costs and annualized costs are estimated in this section for each model unit and each regulatory alternative. In order to assure a common cost basis, cost data from the various sources have been corrected to 1979 values by means of appropriate cost inflation indicators from the "Economic Indicators" sections of Chemical Engineering. For background to this analysis, it is helpful to review information presented in Chapter 6 describing the model units and regulatory alternatives. For example, Table 8-1 restates the model unit equipment handling over 10 percent benzene, and Table 8-2 reviews the inspection intervals and equipment specifications for each regulatory alternative.

8.2 CAPITAL COST ESTIMATES

Capital cost expenditures are required for all of the regulatory alternatives and model units. These costs will be incurred for the purchase of monitoring instruments and control equipment. Two monitoring devices will be purchased at each unit, regardless of the regulatory alternative chosen. This minimum is required to allow for backup if one unit is inoperative. Additional capital costs depend on the number of pieces of affected facilities (potential leak sources) in the model unit and the types of control equipment specified for the regulatory alternative. To calculate these additional costs, data presented in Table 8-3 were accumulated for monitoring and control equipment.

Using the model unit parameters given in Table 8-1 and the capital cost data in Table 8-3, capital costs for each model unit

Table 8-1. MODEL UNIT EQUIPMENT CONTAINING >10 PERCENT BENZENE

Source Type	Number of Components per Model Unit		
	Model A[a]	Model B[b]	Model C[c]
Pumps	5	15	25
Pipeline Valves, Gas[d]			
Block	27	83	138
Control	3	8	13
Pipeline Valves, Liquid[d]			
Block	51	153	256
Control	5	15	24
Safety/Relief Valves, Gas	3	9	16
Open-Ended Valves, Gas	3	7	12
Open-Ended Valves, Liquid	23	72	119
Drains	5	15	25
Sample Connections	9	26	44

[a] Represents an average inventory of equipment for production of ethylbenzene, styrene, cumene, cyclohexane, benzene sulfonic acid, resorcinol, maleic anhydride, or 1 ethylene production unit.

[b] Represents an average inventory of equipment for production of chlorobenzenes, linear alkylbenzenes, or 2 or 3 ethylene production units.

[c] Represents an average inventory of equipment for production of benzene, nitrobenzene, hydroquinone, or 4 or 5 ethylene production units.

[d] From Hydroscience, 6 percent of all valves are control valves; 69 percent of all valves are process valves; so, 6 ÷ 69 or 8.7 percent of process valves are control valves (Ref. 2).

Table 8-2. MONITORING INTERVALS AND EQUIPMENT SPECIFICATIONS FOR BENZENE FUGITIVE REGULATORY ALTERNATIVES

	Regulatory Alternatives[a]							
	II[b]		III		IV		V	
Source[c,d]	Inspection Interval	Equipment Specification	Inspection Interval	Equipment Specification	Inspection Interval	Equipment Specification	Inspection Interval	Equipment Specification
1. Pumps	Yearly[e]	None	Monthly[e]	None	None[e]	Dual Seals[f] and controlled degassing vent	None	Dual Seals[f] and controlled degassing vent
2. Pipeline Valves								
a. Gas Service	Quarterly	None	Monthly	None	Monthly	None	None	Diaphragm or sealed bellows valves
b. Liquid Service	Yearly	None	Monthly	None	Monthly	None	None	Diaphragm or sealed bellows valves
3. Safety/Relief Valves (Gas Service)	Quarterly	None	None	Rupture disks or tie into existing flare	None	Rupture disks or tie into existing flare	None	Rupture disks or tie into existing flare
4. Open-Ended Valves								
a. Gas Service	Quarterly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	None	Diaphragm or sealed bellows valve plus caps, blinds, or plugs
b. Liquid Service	Yearly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	Monthly[g]	Caps, blinds, or plugs	None	Diaphragm or sealed bellows valve plus caps, blinds, or plugs
5. Drains	Yearly	None	Monthly	None	Monthly	None	None	Enclosed active drain systems
6. Sampling Connections	None	None	None	Closed-loop sampling	None	Closed-loop sampling	None	Closed-loop sampling
7. Compressors	Quarterly	None	Monthly	None	None	Mechanical Seals	None	Mechanical Seals
8. Product Accumulator Vessel Vents	None	None	None	Tie into closed control system	None	Tie into closed control system	None	Tie into closed control system

Table 8-2. MONITORING INTERVALS AND EQUIPMENT SPECIFICATIONS FOR BENZENE FUGITIVE REGULATORY ALTERNATIVES (Concluded)

NOTES:

[a] Regulatory Alternative I (baseline) includes no new regulatory specifications and, hence, is not included in this table. Regulatory Alternative VI is not included since it would require that no benzene be emitted from refining and organic chemical industry sources.

[b] Alternative II is equivalent to controls recommended in the refinery CTG for fugitive VOC emissions.

[c] Liquid service safety/relief valves, flanges, wastewater separators, vacuum-producing systems, process unit turnarounds, and cooling towers are not routinely monitored. Wastewater separators, vacuum-producing systems, process unit turnarounds, and cooling towers are not included in this table since there are no available control technologies for these sources.

[d] For all alternatives, the sources would handle organic streams with over 10 percent benzene by weight.

[e] For pumps, instrument monitoring would be supplemented with weekly visual inspections for liquid leakage. If liquid is noted to be leaking from the pump seal, the pump seal will be repaired.

[f] A sensing device should be installed between the dual seals and should be monitored to detect seal failure.

[g] Inspection applies to the valve.

Table 8-3. CAPITAL COST DATA
(May 1979 Dollars)

Item	Capital Cost	Reference
1. Monitoring Instrument	2 x 4,250 = $8,500	1
2. Caps for Open-Ended **Valves**	$50/cap	2, 3, 4[a]
3. Double Mechanical Seals	$590/pump (new) $870/pump (retrofit)	2, 3, 4[b]
4. Barrier Fluid Recirculation System for Double Seals	$1,530/pump	2, 3, 4[b]
5. Degassing Vents	1. 61 m of 5.1 cm carbon steel pipe (installed) $2,700	2, 3, 4[c]
	2. 3 x 5.1 cm valves (installed) $940	2, 3, 4[c]
	3. 1 x 5.1 cm flame arrestor (installed) $450	2, 3, 4[c]
	Total = $4,090/pump[d]	
6. Rupture Disks for **Safety/** Relief Valves	$1,800/relief valve (new) $3,230/relief valve (retrofit)	2, 3, 4, 13, 14[a,e]
7. Closed-Loop Sampling Connections	$480 (new or retrofit)	2, 3, 4[a,d]
8. Sealed Bellows Valves	$3,700/valve (retrofit) $2,500/valve (new)	5

Table 8-3. CAPITAL COST DATA (Concluded)
(May 1979 Dollars)

Item	Capital Cost	Reference
9. Sealed Drain Covers	$1,000/drain	6[f]
10. Replacement Pump	$3,000/pump	7[g]

NOTES:

[a] Plant cost indices were used.

[b] Pump and compressor cost indices were used.

[c] Piping, valve and fitting cost indices were used.

[d] No retrofit penalty.

[e] Cost of rupture disks includes rupture disk, block valve, and replacement of relief valve.

[f] Consists of sealed drain cover and sealed pump drain line.

[g] In retrofitting double seals, it has been assumed that 10 percent of the pumps will have to be replaced. Thus, the following numbers would have to be replaced:
Model A — 1 Pump
Model B — 2 Pumps
Model C — 3 Pumps

size are estimated. Table 8-4 includes capital costs in May 1979 dollar values for new and existing equipment handling more than 10 percent benzene by weight in their organic streams. Regulatory Alternative I represents baseline emission control for units that are assumed to need no additional controls and, as such, will incur no capital costs. Regulatory Alternative II includes capital costs for the purchase of monitoring instruments and the installation of caps on open-ended valves. Capital costs per model unit (existing and new) for Regulatory Alternative II are $10,300 (A), $13,800 (B), and $17,300 (C). In addition to the controls for Regulatory Alternative II, Regulatory Alternative III provides for the installation of rupture disks on gas-service safety/relief valves that vent to atmosphere and the installation of closed-loop sampling connections. Capital costs would increase to the following for existing units: $24,300 (A), $55,400 (B), and $90,100 (C). For new units capital costs would be $20,000 (A), $42,500 (B), and $67,200 (C). The high cost of retrofitting rupture disks on safety/relief valves explains the difference in capital costs between existing and new units. Regulatory Alternative IV specifies that pumps and compressors be equipped with mechanical seals for which degassing vents on pump seal reservoirs are installed. Costs are given for double seal systems for pumps, even though Regulatory Alternatives IV and V specify dual seals (double or tandem). These costs added to the ones for Regulatory Alternative III include the following for existing units: $56,900 (A), $152,900 (B), and $252,500 (C). For new units capital costs would be $51,200 (A), $135,800 (B), and $222,600 (C). Alternative V, which requires leak-less emission control equipment and thus maximum control, includes additional control costs for installing diaphragm or sealed-bellows type valves as well as sealing drain covers. Capital costs for each existing model unit would be increased to the following: $504,100 (A), $1,512,200 (B), and $2,520,200 (C). Capital costs for new model units would be $350,200 (A), $1.052,300 (B), and $1,754,100 (C).

8.3 ANNUALIZED COST ESTIMATES

8.3.1 Derivation of Annualized Cost Estimates

Annualized cost estimates are given in six categories:

Table 8-4. CAPITAL COST ESTIMATES PER MODEL UNIT
(Thousands of May 1979 Dollars)

Capital Cost Item	Regulatory Alternative I	II	III	IV	V
Model Unit A (Existing)					
1. Monitoring Instrument		8.5	8.5	8.5	
2. Caps for Open-Ended Valves		1.8	1.8	1.8	1.8
3. Double Mechanical Seals				4.4	4.4
4. Barrier Fluid Recirculation System for Double Mechanical Seals				7.7	7.7
5. Vents for Barrier Fluid Degassing Reservoirs				20.5	20.5
6. Replacement Pumps					3.0
7. Rupture Disks for Safety/ Safety/Relief Valves			9.7	9.7	9.7
8. Closed Loop Sampling Connections			4.3	4.3	4.3
9. Sealed Bellows, Valves					447.7
10. Hard Piping and Drain Covers					50.0
TOTAL	0.0	10.3	24.3	56.9	504.1

Table 8-4. CAPITAL COST ESTIMATES PER MODEL UNIT (Continued)
(Thousands of May 1979 Dollars)

	Regulatory Alternative				
Capital Cost Item	I	II	III	IV	V
Model Unit A (New)					
1. Monitoring Instrument		8.5	8.5	8.5	
2. Caps for Open-Ended Valves		1.8	1.8	1.8	1.8
3. Double Mechanical Seals				3.0	3.0
4. Barrier Fluid Recirculation System for Double Mechanical Seals				7.7	7.7
5. Vents for Barrier Fluid Degassing Reservoirs				20.5	20.5
6. Rupture Disks for Safety/ Safety/Relief Valves			5.4	5.4	5.4
7. Closed Loop Sampling Connections			4.3	4.3	4.3
8. Sealed Bellows, Valves					302.5
9. Hard Piping and Drain Covers					50.0
TOTAL	0.0	10.3	20.0	51.2	350.2

Table 8-4. CAPITAL COST ESTIMATES PER MODEL UNIT
(Thousands of May 1979 Dollars)

	Regulatory Alternative				
Capital Cost Item	I	II	III	IV	V
Model Unit B (Existing)					
1. Monitoring Instrument		8.5	8.5	8.5	
2. Caps for Open-Ended Valves		5.3	5.3	5.3	5.3
3. Double Mechanical Seals				13.1	13.1
4. Barrier Fluid Recirculation System for Double Mechanical Seals				23.0	23.0
5. Vents for Barrier Fluid Degassing Reservoirs				61.4	61.4
6. Replacement Pumps					6.0
7. Rupture Disks for Safety/Relief Valves			29.1	29.1	29.1
8. Closed Loop Sampling Connections			12.5	12.5	12.5
9. Sealed Bellows, Valves					1346.8
10. Hard Piping and Drain Covers					15.0
TOTAL	0.0	13.8	55.4	152.9	1512.2

Table 8-4. CAPITAL COST ESTIMATES PER MODEL UNIT (Continued)
(Thousands of May 1979 Dollars)

	Regulatory Alternative				
Capital Cost Item	I	II	III	IV	V
Model Unit B (New)					
1. Monitoring Instrument		8.5	8.5	8.5	
2. Caps for Open-Ended Valves		5.3	5.3	5.3	5.3
3. Double Mechanical Seals				8.9	8.9
4. Barrier Fluid Recirculation System for Double Mechanical Seals				23.0	23.0
5. Vents for Barrier Fluid Degassing Reservoirs				61.4	61.4
6. Rupture Disks for Safety/Relief Valves			16.2	16.2	16.2
7. Closed Loop Sampling Connections			12.5	12.5	12.5
8. Sealed Bellows, Valves					910.0
9. Hard Piping and Drain Covers					15.0
TOTAL	0.0	13.8	42.5	135.8	1052.3

Table 8-4. CAPITAL COST ESTIMATES PER MODEL UNIT
(Thousands of May 1979 Dollars)

Capital Cost Item	Regulatory Alternative I	II	III	IV	V
Model Unit C (Existing)					
1. Monitoring Instrument		8.5	8.5	8.5	
2. Caps for Open-Ended Valves		8.8	8.8	8.8	8.8
3. Double Mechanical Seals				21.8	21.8
4. Barrier Fluid Recirculation System for Double Mechanical Seals				38.3	38.3
5. Vents for Barrier Fluid Degassing Reservoirs				102.3	102.3
6. Replacement Pumps					9.0
7. Rupture Disks for Safety/Relief Valves			51.7	51.7	51.7
8. Closed Loop Sampling Connections			21.1	21.1	21.1
9. Sealed Bellows, Valves					2242.2
10. Hard Piping and Drain Covers					25.0
TOTAL	0.0	17.3	90.1	252.5	2520.0

Table 8-4. CAPITAL COST ESTIMATES PER MODEL UNIT (Concluded)
(Thousands of May 1979 Dollars)

	Regulatory Alternative				
Capital Cost Item	I	II	III	IV	V
Model Unit C (New)					
1. Monitoring Instrument		8.5	8.5	8.5	
2. Caps for Open-Ended Valves		8.8	8.8	8.8	8.8
3. Double Mechanical Seals				14.8	14.8
4. Barrier Fluid Recirculation System for Double Mechanical Seals				38.3	38.3
5. Vents for Barrier Fluid Degassing Reservoirs				102.3	102.3
6. Rupture Disks for Safety/ Relief Valves			28.8	28.8	28.8
7. Closed Loop Sampling Connections			21.1	21.1	21.1
8. Sealed Bellows, Valves					1515.0
9. Hard Piping and Drain Covers					25.0
TOTAL	0.0	17.3	67.2	222.6	1754.1

(1) monitoring instrument annualized capital charges, and material, maintenance, and calibration expenses,

(2) emissions control equipment maintenance and capital charges,

(3) leak detection labor,

(4) repair labor,

(5) administration and support, and

(6) initial control program startup.

Annualized capital charges include depreciation, interest, property taxes, and insurance. Depreciation and interest are computed by the use of a Capital Recovery Factor (CRF), based on the lifetime of the equipment and the annual interest rate. Property taxes and insurance are also included and are estimated at 4 percent of the total capital cost. These items are calculated by means of the formula:

$$C = C_1 + C_2$$

where C = total annualized costs; C_1 = annual depreciation and interest charges; and C_2 = property taxes and insurance. Now C_1 and C_2 are described as:

$C_1 = C_c \times (CRF)$ and $C_2 = C_c \times (4\%)$

where: C_c = capital cost of the equipment

$$CRF = \frac{i\ (1+i)^n}{(1+i)^n-1}$$

where: i = annual interest rate (10%)

n = lifetime of equipment, years (n=6 for the monitoring instrument, and n=10 for control equipment)

Annualized leak detection and repair labor costs are derived by means of the formula:

$$L = L_1 + L_2$$

where L = total annual leak detection and repair labor costs; L_1 = annual leak detection cost; and L_2 = annual repair cost. Now L_1 and L_2 are described as:

$L_1 = (AxBxDxE)xN$ and $L_2 = FxGxE$

where: A = Number of model unit components affected
B = Monitoring time, hours (leak detection)
D = Times monitored per year
E = Labor cost, \$/hr = \$15.50/hr
F = Estimated number of leaks per year
G = Repair time, hours (maintenance)
N = Number of workers involved in monitoring = 2

Annualized administrative and support costs are estimated at 40 percent of the leak detection and repair labor costs.

Finally, the cost of repairing leaks found during an initial unit survey is also computed. This cost is amortized by employing a Capital Recovery Factor using the control equipment lifetime (10 years), and an annual interest rate of 10 percent.

Tables 8-5 through 8-8 give annual leak detection and repair labor costs (in May 1979 values) for Regulatory Alternatives II through V. Total annual leak detection labor costs range from \$30 (Unit A, Regulatory Alternative V) to \$4,850 (Unit C, Regulatory Alternative III). Total annual repair labor costs range from \$0 (Units A, B, and C, Regulatory Alternative V) to \$5,750 (Unit C, Regulatory Alternative III). Leak detection and repair labor costs do not follow a linear relationship for increasing levels of benzene emission control. Lower monitoring (leak detection) costs for Regulatory Alternative V in comparison with the other Regulatory Alternatives result from the fact that there would be virtually no leaks if Regulatory Alternative V were applied. The only monitoring performed is the weekly visual inspection of pumps. Since this Regulatory Alternative represents leakless emission control, no repair labor costs would be incurred.

Estimates of credits from the recovery of benzene emissions have been made from refining and organic chemical operations, based on the market price of benzene as of May 1979 (\$370/Mg or \$1.30/gal).[9] Table 8-9 presents the recovered product credits derived from the market price of the recovered product and the quantity of total VOC emissions reduced as a result of each regulatory alternative. Recovered product credits range from \$4,740 (Unit A, Regulatory

Table 8-5. MONITORING AND MAINTENANCE LABOR-HOUR REQUIREMENTS FOR REGULATORY ALTERNATIVE II

Source Type	MONITORING									MAINTENANCE						
	Number of Components Per Model Unit			Type of Monitoring	Monitoring Time Per Person[a] (Minutes)	Times Monitored Per Year	Monitoring Labor-Hours Required			Estimated Number of Leaks[b]			Repair Time (Hours)	Maintenance Labor-Hours Required		
	A	B	C				A	B	C	A	B	C		A	B	C
Pumps	5	15	25	Instrument	5	1	0.8	2.5	4.2	1	1	1	80	80	80	80
				Visual	0.5	52	2.2	6.5	10.8							
Valves Gas	34	100	167	Instrument	1	4	4.5	13.3	22.3	1	4	7	1.13	1	5	8
Liquid	87	264	439	Instrument	1	1	2.9	8.8	14.6	2	6	11	1.13	2	7	12
Safety/ Relief Valves	4	11	19	Instrument	8	4	4.3	11.7	20.3	c	c	c	0	0	0	0
Drains	5	15	25	Instrument	1	1	0.2	0.5	0.8	1	1	1	4	4	4	4

	A	B	C		A	B	C
Total Monitoring Hours =	14.9	43.3	73.0	Total Maintanence Hours =	87	96	104
x $15.50/hour				x $15.50/hour			
Total Monitoring Dollars =	230	670	1130	Total Maintenance Dollars =	1350	1490	1610

[a] Instrument monitoring requires a two-person team. Visual monitoring requires one person.

[b] Recurrence factors of 0.6, 0.4, and 0.2 have been applied for monthly, quarterly, and annual instrument inspections. It is assumed that 5 percent of leaks initially detected recur each month (0.5 x 12 = 0.6), that 10 percent of leaks initially detected recur each quarter (.10 x 4 = 0.4), and that 20 percent of leaks initially detected recur annually (.20 x 1 = 0.2)

[c] These leaks are repaired by routine maintenance at no incremental increase in manpower requirements. Safety/relief valves are normally reset during routine maintenance without a leak detection and repair program. (Reference 8).

Table 8-6. MONITORING AND MAINTENANCE LABOR-HOUR REQUIREMENTS FOR REGULATORY ALTERNATIVE III

	MONITORING									MAINTENANCE						
	Number of Components Per Model Unit						Monitoring Labor-Hours Required			Estimated Number of Leaks[b]				Maintenance Labor-Hours Required		
Source Type	A	B	C	Type of Monitoring	Monitoring Time Per Person[a] (Minutes)	Times Monitored Per Year	A	B	C	A	B	C	Repair Time (Hours)	A	B	C
Pumps	5	15	25	Instrument	5	12	10.0	30.0	50.0	1	2	4	80	80	160	320
				Visual	0.5	52	2.2	6.5	10.8							
Valves Gas	34	100	167	Instrument	1	12	13.6	40.0	66.8	2	6	10	1.13	2	7	11
Liquid	87	264	439	Instrument	1	12	34.8	105.6	175.6	6	19	32	1.13	7	21	36
Safety/ Relief Valves	4	11	19	Instrument	8	0	0.0	0.0	0.0	--	--	--	0	0	0	0
Drains	5	15	25	Instrument	1	12	2.0	6.0	10.0	1	1	1	4	4	4	4

	A	B	C		A	B	C
Total Monitoring Hours =	62.6	188.1	313.2	Total Maintanence Hours =	93	192	371
x $15.50/hour				x $15.50/hour			
Total Monitoring Dollars =	970	2920	4850	Total Maintenance Dollars =	1440	2980	5750

[a] Instrument monitoring requires a two-person team. Visual monitoring requires one person.

[b] Recurrence factors of 0.6, 0.4 and 0.2 have been applied for monthly, quarterly, and annual instrument inspections. It is assumed that 5 percent of leaks initially detected recur each month (0.5 x 12 = 0.6), that 10 percent of leaks initially detected recur each quarter (.10 x 4 = 0.4), and that 20 percent of leaks initially detected recur annually (.20 x 1 = 0.2).

Table 8-7. MONITORING AND MAINTENANCE LABOR-HOUR REQUIREMENTS FOR REGULATORY ALTERNATIVE IV

Source Type	MONITORING										MAINTENANCE						
	Number of Components Per Model Unit			Type of Monitoring	Monitoring Time Per Person[a] (Minutes)	Times Monitored Per Year	Monitoring Labor-Hours Required			Estimated Number of Leaks[b]			Repair Time (Hours)	Maintenance Labor-Hours Required		
	A	B	C				A	B	C	A	B	C		A	B	C
Pumps	5	15	25	Instrument	5	0	0	0	0	0	0	0	80	0	0	0
				Visual	0.5	52	2.2	6.5	10.8							
Valves Gas	34	100	167	Instrument	1	12	13.6	40.0	66.8	2	6	10	1.13	2	7	11
Liquid	87	264	439	Instrument	1	12	34.8	105.6	175.6	6	19	32	1.13	7	21	36
Safety/ Relief Valves	4	11	19	Instrument	8	0	0	0	0	0	0	0	0	0	0	0
Drains	5	15	25	Instrument	1	12	2.0	6.0	10.0	1	1	1	4	4	4	4

	A	B	C		A	B	C
Total Monitoring Hours =	52.6	158.1	263.2	Total Maintanence Hours =	13	32	51
x $15.50/hour				x $15.50/hour			
Total Monitoring Dollars =	820	2450	4080	Total Maintenance Dollars =	200	500	790

[a] Instrument monitoring requires a two-person team. Visual monitoring requires one person.

[b] Recurrence factors of 0.6, 0.4, and 0.2 have been applied for monthly, quarterly, and annual instrument inspections. It is assumed that 5 percent of leaks initially detected recur each month (0.5 x 12 = 0.6), that 10 percent of leaks initially detected recur each quarter (.10 x 4 = 0.4), and that 20 percent of leaks initially detected recur annually (.20 x 1 = 0.2).

Table 8-8. MONITORING AND MAINTENANCE LABOR-HOUR REQUIREMENTS FOR REGULATORY ALTERNATIVE V

Source Type	MONITORING									MAINTENANCE						
	Number of Components Per Model Unit			Type of Monitoring	Monitoring Time Per Person[a] (Minutes)	Times Monitored Per Year	Monitoring Labor-Hours Required			Estimated Number of Leaks			Repair Time (Hours)	Maintenance Labor-Hours Required		
	A	B	C				A	B	C	A	B	C		A	B	C
Pumps	5	15	25	Instrument	5	0	0	0	0	0	0	0	80	0	0	0
				Visual	0.5	52	2.2	6.5	10.8							
Valves Gas	34	100	167	Instrument	1	0	0	0	0	0	0	0	1.13	0	0	0
Liquid	87	264	439	Instrument	1	0	0	0	0	0	0	0	1.13	0	0	0
Safety/Relief Valves	4	11	19	Instrument	8	0	0	0	0	0	0	0	0	0	0	0
Drains	5	15	25	Instrument	1	0	0	0	0	0	0	0	4	0	0	0

Total Monitoring Hours = 2.2 6.5 10.8

x $15.50/hour.

Total Monitoring Dollars = 30 100 170

Total Maintanence Hours = 0 0 0

x $15.50/hour

Total Maintenance Dollars = 0 0 0

[a] Instrument monitoring requires a two-person team. Visual monitoring requires one person.

Table 8-9. RECOVERED PRODUCT CREDITS

Regulatory Alternative	Model Unit A				Model Unit B				Model Unit C			
	VOC Emissions[a] (Mg/Year)	Emission Reduction From Uncontrolled (Mg/Year)	Recovery Credit[b] (Mg/Year)	Recovered Product Value[c] ($/Year)	VOC Emissions[a] (Mg/Year)	Emission Reduction From Uncontrolled (Mg/Year)	Recovery Credit[b] (Mg/Year)	Recovered Product Value[c] ($/Year)	VOC Emissions[a] (Mg/Year)	Emission Reduction From Uncontrolled (Mg/Year)	Recovery Credit[b] (Mg/Year)	Recovered Product Value[c] ($/Year)
I	29.3	----	----	----	82.9	----	----	----	129.7	----	----	----
II	13.7	15.6	12.8	4,740	36.0	46.9	38.5	14,200	50.8	78.9	64.1	23,700
III	9.2	20.1	15.5	5,740	22.6	60.3	46.5	17,200	28.0	101.7	77.4	28,700
IV	8.0	21.3	16.8	6,220	18.9	64.0	50.3	18,600	21.7	108.00	83.7	31,000
V	4.6[d]	24.7	19.3	7,140	8.8	74.1	57.9	21,400	5.0[d]	124.7	96.5	35,700
VI	0.0	29.3	----	----	0.0	82.9	----	----	0.0	129.7	----	----

[a] Includes emissions from equipment handling less than 10 percent benzene.

[b] Does not include emissions from **safety/relief valves or drains, since these may not be recovered**.

[c] This value is obtained by multiplying the recovery credit in Mg per year by $370 per Mg (second quarter, 1979 value for benzene, Ref. 9).

[d] "Residue" from uncontrolled equipment (less than 10 percent benzene).

Alternative II) to $35,700 (Unit C, Regulatory Alternative V) per year, the credits being a function of model unit size and the regulatory alternative.

The annualized costs associated with the initial screening survey and the resultant leak repairs are detailed for Regulatory Alternatives II, III, and IV per model unit in Table 8-10. Total repair labor costs ranging from $280 (Model A, Regulatory Alternative IV) to $8,730 (Model C, Regulatory Alternatives II and III) are multiplied by a CRF of 0.25 (10 years, 10 percent) to yield annual repair labor costs ranging from $70 (Model A, Regulatory Alternative IV) to $2,180 (Model C, Regulatory Alternatives II and III).

Annualized costs for implementing Regulatory Alternatives I through V for three model unit sizes are given in Table 8-11. Each model unit is classified as either existing or new. Regulatory Alternative I is assumed to need no additional controls, thus there are no annualized costs. Annualized control costs for the existing units range from $8,100 (Model A, Regulatory Alternative II) to $644,700 (Model C, Regulatory Alternative V). For new units, which do not incur the high retrofitting costs of existing units, the range is from $7,700 (Model A, Regulatory Alternative II) to $448,600 (Model C, Regulatory Alternative V).

8.3.2 Cost-Effectiveness

A cost-effectiveness analysis was performed to determine which regulatory alternative reduces the greatest benzene emissions at the least cost. Total annual costs due to each regulatory alternative were divided by the annual benzene emission reduction achieved under that Regulatory Alternative to generate a cost-effectiveness figure. Table 8-12 lists benzene emission reductions per model unit for each regulatory alternative, while Tables 8-13 and 8-14 present the cost-effectiveness for the existing and new model units, respectively. Baseline or uncontrolled benzene emissions, represented by Regulatory Alternative I, per model unit are estimated to be 18.6 Mg/year (A), 44.7 Mg/year (B), and 97.1 Mg/year (C). Under Regulatory Alternative II, benzene emissions from Model Unit A are estimated to decrease 53 percent from the baseline emissions (from 18.6 Mg/year to 8.7 Mg/year). Similarly, benzene emission reductions of 57 and 61 percent for Model

Table 8-10. INITIAL SURVEY START-UP COSTS FOR REGULATORY ALTERNATIVE II

Source Type	Number of Components per Model Unit			Percent of Sources Leaking in Initial Survey	Estimated Number of Leaks			Repair Time (Hours)	Repair Labor Hours		
	A	B	C		A	B	C		A	B	C
Pumps	5	15	25	23	1	3	6	80	80	240	480
Valves											
Gas	34	100	167	10	3	10	17	1.13	3	11	19
Liquid	87	264	439	12	10	32	53	1.13	11	36	60
Safety/relief Valves	4	11	19	8	a	a	a	0	0	0	0
Drains	5	15	25	4	1	1	1	4	4	4	4
								Total Hours =	98	291	563
									x $15.50/hour		
								TOTAL =	1520	4510	8730
									x CRF = 0.25 (10 year, 10 Percent)		
								Annualized[b] =	380	1130	2180

Table 8-10. INITIAL SURVEY START-UP COSTS FOR REGULATORY ALTERNATIVE III (Continued)

Source Type	Number of Components Per Unit			Percent Sources Leaking in Initial Survey	Estimated Number of Leaks			Repair Time (Hours)	Repair Labor Hours		
	A	B	C		A	B	C		A	B	C
Pumps	5	15	25	23	1	3	6	80	80	240	480
Valves											
Gas	34	100	167	10	3	10	17	1.13	3	11	19
Liquid	87	264	439	12	10	32	53	1.13	11	36	60
Drains	5	15	25	4	1	1	1	4	4	4	4

Total Hours = 98 291 563

x $15.50/hour

TOTAL = 1520 4510 8730

x CRF = 0.25 (10 year, 10 Percent)

Annualized[b] = 380 1130 2180

Table 8-10. INITIAL SURVEY START-UP COSTS FOR REGULATORY ALTERNATIVE IV (Continued)

Source Type	Number of Components Per Unit			Percent Sources Leaking in Initial Survey	Estimated Number of Leaks			Repair Time (Hours)	Repair Labor Hours		
	A	B	C		A	B	C		A	B	C
Valves											
Gas	34	100	167	10	3	10	17	1.13	3	11	19
Liquid	87	264	439	12	10	32	53	1.13	11	36	60
Drains	5	15	25	4	1	1	1	4	4	4	4
								Total Hours =	18	51	83
								x $15.50/hour			
								TOTAL =	280	790	1290
								x CRF = 0.25 (10 year, 10 Percent)			
								Annualized[b] =	70	200	320

Table 8-10. INITIAL SURVEY START-UP COSTS (Concluded)

NOTES:

[a] Leaks are repaired by routine maintenance at no incremental increase in manpower requirements. Safety/relief valves are normally reset during routine maintenance without a leak detection and repair program.

[b] Since there are no one-time start-up costs, these numbers can be capitalized using the Capital Recovery Factor (CRF) method.

Table 8-11. ANNUALIZED CONTROL COST ESTIMATES PER MODEL UNIT[a]
(Thousands of May 1979 Dollars)

Model Unit: A (Existing)

Cost Item	I	II	III	IV	V
Annualized Capital Charges					
1. Control Equipment					
a. Instrument[b]		2.0 0.3	2.0 0.3	2.0 0.3	0.0 0.3
b. Caps[c]					
c. Double Seals				1.7	1.7
• Seals				0.2	0.2
• Installation				1.2	1.2
d. Seal Oil System[d]				3.4	3.4
e. Vents-Pumps and Compressors					0.5
f. Replacement Pumps[e]					
g. Rupture Disks[f]			0.3	0.3	0.3
• Disks			1.5	1.5	1.5
• Installation			0.7	0.7	0.7
h. Closed-Loop Sampling[g]					72.9
i. Sealed-Bellows Valves[h]					0.8
j. Hard Piping[g,i]					
2. Initial Leak Repair[j]		0.4	0.4	0.1	0.0
Operating Costs					
1. Maintenance Charges					
a. Instrument		2.7 0.1	2.7 0.1	2.7 0.1	0.0 0.1
b. Caps				0.2	0.2
c. Double Seals				0.3	0.3
d. Seal Oil System				0.8	0.8
e. Vents-Pumps and Compressors					0.1
f. Replacement Pumps			0.4	0.4	0.4
g. Rupture Disks			0.2	0.2	0.2
h. Closed-Loop Sampling					17.9
i. Sealed-Bellows Valves					0.2
j. Hard Piping					
2. Miscellaneous (Taxes, Insurance, Administration)					
a. Instrument		0.3 0.1	0.3 0.1	0.3 0.1	0.0 0.1
b. Caps				0.2	0.2
c. Double Seals				0.4	0.4
d. Seal Oil System				1.0	1.0
e. Vents-Pumps and Compressors					0.2
f. Replacement Pumps			0.5	0.5	0.5
g. Rupture Disks			0.2	0.2	0.2
h. Closed-Loop Sampling					22.4
i. Sealed-Bellows Valves					0.3
j. Hard Piping					
3. Labor					
a. Leak Detection Labor		0.2	1.0	0.8	0.0
b. Repair Labor		1.4	1.4	0.2	0.0
c. Administrative and Support		0.6	1.0	0.4	0.0
Total Before Credit	0.0	8.1	13.1	20.2	129.0

Table 8-11. ANNUALIZED CONTROL COST ESTIMATES PER MODEL UNIT[a] (Continued) (Thousands of May 1979 Dollars)

Model Unit: A (New)

Cost Item	I	II	III	IV	V
Annualized Capital Charges					
1. Control Equipment					
a. Instrument[b]		2.0	2.0	2.0	0.0
b. Caps[c]		0.3	0.3	0.3	0.3
c. Double Seals					
• Seals				1.0	1.0
• Installation				0.2	0.2
d. Seal Oil System[d]				1.2	1.2
e. Vents-Pumps and Compressors				3.4	3.4
f. Rupture Disks[f]					
• Disks			0.3	0.3	0.3
• Installation			0.8	0.8	0.8
g. Closed-Loop Sampling[g]			0.7	0.7	0.7
h. Sealed-Bellows Valves[h]					49.3
i. Hard Piping[g,i]					0.8
2. Initial Leak Repair[j]			0.0	0.0	0.0
Operating Costs					
1. Maintenance Charges					
a. Instrument		2.7	2.7	2.7	0.0
b. Caps		0.1	0.1	0.1	0.1
c. Double Seals				0.1	0.1
d. Seal Oil System				0.3	0.3
e. Vents-Pumps and Compressors				0.8	0.8
f. Rupture Disks			0.2	0.2	0.2
g. Closed-Loop Sampling			0.2	0.2	0.2
h. Sealed-Bellows Valves					12.1
i. Hard Piping					0.2
2. Miscellaneous (Taxes, Insurance, Administration)					
a. Instrument		0.3	0.3	0.3	0.0
b. Caps		0.1	0.1	0.1	0.1
c. Double Seals				0.2	0.2
d. Seal Oil System				0.4	0.4
e. Vents-Pumps and Compressors				1.0	1.0
f. Rupture Disks			0.3	0.3	0.3
g. Closed-Loop Sampling			0.2	0.2	0.2
h. Sealed-Bellows Valves					15.1
i. Hard Piping					0.3
3. Labor					
a. Leak Detection Labor		0.2	1.0	0.8	0.0
b. Repair Labor		1.4	1.4	0.2	0.0
c. Administrative and Support		0.6	1.0	0.4	0.0
Total Before Credit	0.0	7.7	11.6	18.2	89.6

Table 8-11. ANNUALIZED CONTROL COST ESTIMATES PER MODEL UNIT[a] (Continued) (Thousands of May 1979 Dollars)

Model Unit: B (Existing)

Cost Item	I	II	III	IV	V
Annualized Capital Charges					
1. Control Equipment					
a. Instrument[b]		2.0	2.0	2.0	0.0
b. Caps[c]		0.8	0.8	0.8	0.8
c. Double Seals					
● Seals				5.0	5.0
● Installation				0.7	0.7
d. Seal Oil System[d]				3.7	3.7
e. Vents-Pumps and Compressors				9.9	9.9
f. Replacement Pumps[e]					1.0
g. Rupture Disks[f]					
● Disks			1.1	1.1	1.1
● Installation			4.3	4.3	4.3
h. Closed-Loop Sampling[g]			2.1	2.1	2.1
i. Sealed-Bellows Valves[h]					219.5
j. Hard Piping[g,i]					
2. Initial Leak Repair[j]		1.1	1.1	0.[illegible]	0.0
Operating Costs					
1. Maintenance Charges					
a. Instrument		2.7	2.7	2.7	0.0
b. Caps		0.2	0.2	0.2	0.2
c. Double Seals				0.5	0.5
d. Seal Oil System				0.9	0.9
e. Vents-Pumps and Compressors				2.5	2.5
f. Replacement Pumps					0.2
g. Rupture Disks			1.2	1.2	1.2
h. Closed-Loop Sampling			0.5	0.5	0.5
i. Sealed-Bellows Valves					53.9
j. Hard Piping					0.6
2. Miscellaneous (Taxes, Insurance, Administration)					
a. Instrument		0.3	0.3	0.3	0.0
b. Caps		0.3	0.3	0.3	0.3
c. Double Seals				0.7	0.7
d. Seal Oil System				1.2	1.2
e. Vents-Pumps and Compressors				3.1	3.1
f. Replacement Pumps					0.3
g. Rupture Disks			1.4	1.4	1.4
h. Closed-Loop Sampling			0.6	0.6	0.6
i. Sealed-Bellows Valves					67.3
j. Hard Piping					0.8
3. Labor					
a. Leak Detection Labor		0.7	2.9	2.5	0.0
b. Repair Labor		1.5	3.0	0.5	0.0
c. Administrative and Support		0.9	2.4	1.2	0.0
Total Before Credit	0.0	10.5	26.9	50.1	386.7

Table 8-11. ANNUALIZED CONTROL COST ESTIMATES PER MODEL UNIT[a] (Continued)
(Thousands of May 1979 Dollars)

Model Unit: B (New)

Cost Item	I	II	III	IV	V
Annualized Capital Charges					
1. Control Equipment					
a. Instrument[b]		2.0	2.0	2.0	0.0
b. Caps[c]		0.8	0.8	0.8	0.8
c. Double Seals					
● Seals				3.0	3.0
● Installation				0.6	0.6
d. Seal Oil System[d]				3.7	3.7
e. Vents-Pumps and Compressors				9.9	9.9
f. Rupture Disks[f]					
● Disks			1.1	1.1	1.1
● Installation			2.4	2.4	2.4
g. Closed-Loop Sampling[g]			2.1	2.1	2.1
h. Sealed-Bellows Valves[h]					148.3
i. Hard Piping[g,i]					2.4
2. Initial Leak Repair[j]		0.0	0.0	0.0	0.0
Operating Costs					
1. Maintenance Charges					
a. Instrument		2.7	2.7	2.7	0.0
b. Caps		0.2	0.2	0.2	0.2
c. Double Seals				0.4	0.4
d. Seal Oil System				0.9	0.9
e. Vents-Pumps and Compressors				2.5	2.5
f. Rupture Disks			0.6	0.6	0.6
g. Closed-Loop Sampling			0.5	0.5	0.5
h. Sealed-Bellows Valves					36.4
i. Hard Piping					0.6
2. Miscellaneous (Taxes, Insurance, Administration)					
a. Instrument		0.3	0.3	0.3	0.0
b. Caps		0.3	0.3	0.3	0.3
c. Double Seals				0.4	0.4
d. Seal Oil System				1.2	1.2
e. Vents-Pumps and Compressors				3.1	3.1
f. Rupture Disks			0.8	0.8	0.8
g. Closed-Loop Sampling			0.6	0.6	0.6
h. Sealed-Bellows Valves					45.5
i. Hard Piping					0.8
3. Labor					
a. Leak Detection Labor		0.7	2.9	2.5	0.0
b. Repair Labor		1.5	3.0	0.5	0.0
c. Administrative and Support		0.9	2.4	1.2	0.0
Total Before Credit	0.0	9.4	22.7	44.3	269.1

Table 8-11. ANNUALIZED CONTROL COST ESTIMATES PER MODEL UNIT[a] (Continued)
(Thousands of May 1979 Dollars)

Model Unit: C (Existing)

Cost Item	I	II	III	IV	V
Annualized Capital Charges					
1. Control Equipment					
a. Instrument[b]		2.0	2.0	2.0	0.0
b. Caps[c]		1.4	1.4	1.4	1.4
c. Double Seals					
● Seals				8.3	8.3
● Installation				1.2	1.2
d. Seal Oil System[d]				6.2	6.2
e. Vents-Pumps and Compressors				16.7	16.7
f. Replacement Pumps[e]					1.4
g. Rupture Disks[f]					
● Disks			1.9	1.9	1.9
● Installation			7.8	7.8	7.8
h. Closed-Loop Sampling[g]			3.4	3.4	3.4
i. Sealed-Bellows Valves[h]					365.5
j. Hard Piping[g,i]					4.0
2. Initial Leak Repair[j]		2.2	2.2	0.3	0.0
Operating Costs					
1. Maintenance Charges					
a. Instrument		2.7	2.7	2.7	0.0
b. Caps		0.4	0.4	0.4	0.4
c. Double Seals				0.9	0.9
d. Seal Oil System				1.6	1.6
e. Vents-Pumps and Compressors				4.1	4.1
f. Replacement Pumps					0.4
g. Rupture Disks			2.0	2.0	2.0
h. Closed-Loop Sampling			0.8	0.8	0.8
i. Sealed-Bellows Valves					89.7
j. Hard Piping					1.0
2. Miscellaneous (Taxes, Insurance, Administration)					
a. Instrument		0.3	0.3	0.3	0.0
b. Caps		0.4	0.4	0.4	0.4
c. Double Seals				1.1	1.1
d. Seal Oil System				1.9	1.9
e. Vents-Pumps and Compressors				5.1	5.1
f. Replacement Pumps					0.5
g. Rupture Disks			2.5	2.5	2.5
h. Closed-Loop Sampling			1.1	1.1	1.1
i. Sealed-Bellows Valves					112.1
j. Hard Piping					1.3
3. Labor					
a. Leak Detection Labor		1.1	4.9	4.1	0.0
b. Repair Labor		1.6	5.8	0.8	0.0
c. Administrative and Support		1.1	4.3	2.0	0.0
Total Before Credit		13.2	43.9	81.0	644.7

Table 8-11. ANNUALIZED CONTROL COST ESTIMATES PER MODEL UNIT[a] (Concluded) (Thousands of May 1979 Dollars)

Model Unit: C (New)

Cost Item	I	II	III	IV	V
Annualized Capital Charges					
1. Control Equipment					
a. Instrument[b]		2.0	2.0	2.0	0.0
b. Caps[c]		1.4	1.4	1.4	1.4
c. Double Seals					
● Seals				5.0	5.0
● Installation				1.0	1.0
d. Seal Oil System[d]				6.2	6.2
e. Vents-Pumps and Compressors				16.7	16.7
f. Rupture Disks[f]					
● Disks			1.9	1.9	1.9
● Installation			4.2	4.2	4.2
g. Closed-Loop Sampling[g]			3.4	3.4	3.4
h. Sealed-Bellows Valves[h]					246.9
i. Hard Piping[g,i]					4.0
2. Initial Leak Repair[j]		0.0	0.0	0.0	0.0
Operating Costs					
1. Maintenance Charges					
a. Instrument		2.7	2.7	2.7	0.0
b. Caps		0.4	0.4	0.4	0.4
c. Double Seals				0.6	0.6
d. Seal Oil System				1.6	1.6
e. Vents-Pumps and Compressors				4.1	4.1
f. Rupture Disks			1.1	1.1	1.1
g. Closed-Loop Sampling			0.8	0.8	0.8
h. Sealed-Bellows Valves					60.6
i. Hard Piping					1.0
2. Miscellaneous (Taxes, Insurance, Administration)					
a. Instrument		0.3	0.3	0.3	0.0
b. Caps		0.4	0.4	0.4	0.4
c. Double Seals				0.7	0.7
d. Seal Oil System				1.9	1.9
e. Vents-Pumps and Compressors				5.1	5.1
f. Rupture Disks			1.4	1.4	1.4
g. Closed-Loop Sampling			1.1	1.1	1.1
h. Sealed-Bellows Valves					75.8
i. Hard Piping					1.3
3. Labor					
a. Leak Detection Labor		1.1	4.9	4.1	0.0
b. Repair Labor		1.6	5.8	0.8	0.0
c. Administrative and Support		1.1	4.3	2.0	0.0
Total Before Credit		11.0	36.1	70.9	448.6

Table 8-11. ANNUALIZED COST ESTIMATES PER MODEL UNIT (Continued)

NOTES:

[a]Cost Factors Used in Computing Annual Costs: (Ref. 2, pp. IV-3 through IV-10)

1. Instrument
   a. Capital Charges
      i. Cost = 2 x $4,250
      ii. Operating Life = 6 Years
      iii. Annual Interest = 10 Percent
      iv. CRF = 0.23
      v. Miscellaneous = 0.04
   b. Materials and Maintenance
      i. Cost = $2,700 Per Year

2. Control Equipment
   a. Capital Charges
   b. Operating Life = 10 Years (2 yrs. for double seal & rupture disk)
   c. Annual Interest = 10 Percent
   d. CRF = 0.16 (0.58 for double seal and rupture disk)
   e. Miscellaneous = 0.04
   f. Maintenance = 0.05

3. Administration and Support = 40 Percent of Leak Detection and Repair Labor Cost

[b]Cost is for Century Systems Corporation's Organic Vapor Analyzer (Model OVA-108).

[c]Used to seal open-ended valves.

[d]Used as auxilliary for double seal.

Table 8-11. ANNUALIZED COST ESTIMATES PER MODEL UNIT (Concluded)

NOTES: (Concluded)

[e] In retrofitting double seals, it has been assumed that 10 percent of the pumps will need to be replaced. Thus, the following numbers of pumps would be replaced:
Model A -- 1 pump
Model B -- 2 pumps
Model C -- 3 pumps

[f] Cost includes rupture disk, block valve, and replacement of safety/ relief valve.

[g] Cost is for new or retrofitted installation.

[h] Used for control valves.

[i] Consists of sealed cover on drain with line leading to pump.

[j] Where equipment standards are applied, as in Regulatory Alternatives IV and V, the amount of leak detection and repair labor decreases.

[k] Based on an average price of $370/Mg (Ref. 9).

[l] Numbers in parentheses represent savings (net credit).

Table 8-12. BENZENE EMISSION REDUCTIONS

Regulatory Alternative	Model Unit A			Model Unit B			Model Unit C		
	VOC Emission[a] (Mg/Year)	Benzene Emission[a] (Mg/Year)	Benzene Emission Reduction[b] (Mg/Year)	VOC Emission[a] (Mg/Year)	Benzene Emission[a] (Mg/Year)	Benzene Emission Reduction[b] (Mg/Year)	VOC Emission[a] (Mg/Year)	Benzene Emission[a] (Mg/Year)	Benzene Emission Reduction[b] (Mg/Year)
I	29.3	18.6	----	82.9	44.7	----	129.7	97.1	----
II	13.7	8.7	9.9	36.0	19.3	25.4	50.8	38.2	58.9
III	9.2	5.9	12.7	22.6	12.1	32.6	28.0	21.2	75.9
IV	8.0	5.1	13.5	18.9	10.1	34.6	21.7	16.5	80.6
V	4.6	2.9	15.7	8.8	4.6	40.1	5.0	4.0	93.1
VI	0.0	0.0	18.6	0.0	0.0	44.7	0.0	0.0	97.1

[a] Calculations of VOC and benzene emissions for each model unit and regulatory alternative are presented in EPA Docket Number A-79-27-II-B.

[b] Benzene emission reductions are calculated for each model unit as the difference between the benzene emissions for the baseline alternative (I) and each of the other alternatives (II-VI).

Table 8-13. COST-EFFECTIVENESS FOR EXISTING MODEL UNITS

	Model Unit A					Model Unit B					Model Unit C				
Regulatory Alternative	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Total Capital Cost ($1,000)[a]	0.0	10.3	24.3	56.9	504.1	0.0	13.8	55.4	152.9	1512.2	0.0	17.3	90.1	252.5	2520.5
Total Annualized Cost ($1,000)[b]	0.0	8.1	13.1	20.2	129.0	0.0	10.5	26.9	50.1	386.7	0.0	13.2	43.9	81.0	644.7
Total Annual Credit ($1,000)[c,d]	0.0	(4.7)	(5.7)	(6.2)	(7.1)	0.0	(14.2)	(17.2)	(18.6)	(21.4)	0.0	(23.7)	(28.7)	(31.0)	(35.7)
Net Annualized Cost ($1,000)[d,e]	0.0	3.4	7.4	14.0	121.9	0.0	(3.7)	9.7	31.5	365.3	0.0	(10.5)	15.2	50.0	609.0
Total Benzene Reduction[f] (Mg/Year)	----	9.9	12.7	13.5	15.7	----	25.4	32.6	34.6	40.1	----	58.9	75.9	80.6	93.1
Cost-Effectiveness[g] (Net Annualized $1,000/Mg Benzene)	----	0.34	0.58	1.0	7.8	----	0.0	0.30	0.91	9.1	----	0.0	0.20	0.62	6.5

[a] From Table 8-4.

[b] From Table 8-11.

[c] From Table 8-9 - Recovered product credit is based on VOC emission reductions from the baseline Alternative I.

[d] Numbers in parentheses represent savings.

[e] Net annualized cost is calculated as the difference between the total annualized cost (Table 8-11) and the recovered product credit (Table 8-9) for each model unit and regulatory alternative.

[f] From Table 8-12.

[g] Calculated by dividing the net annualized cost ($1000) by the total benzene reduction for each model unit and regulatory alternative.

Table 8-14. COST-EFFECTIVENESS FOR NEW MODEL UNITS

	Model Unit A					Model Unit B					Model Unit C				
Regulatory Alternative	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Total Capital Cost ($1,000)[a]	0.0	10.3	20.0	51.2	350.2	0.0	13.8	42.5	135.8	1052.3	0.0	17.3	67.2	222.6	1754.1
Total Annualized Cost ($1,000)[b]	0.0	7.7	11.6	18.2	89.6	0.0	9.4	22.7	44.3	269.1	0.0	11.0	36.1	70.9	448.6
Total Annual Credit ($1,000)[c,d]	0.0	(4.7)	(5.7)	(6.2)	(7.1)	0.0	(14.2)	(17.2)	(18.6)	(21.4)	0.0	(23.7)	(28.7)	(31.0)	(35.7)
Net Annualized Cost ($1,000)[d,e]	0.0	3.0	5.9	12.0	82.5	0.0	(4.8)	5.5	25.7	247.7	0.0	(12.7)	7.4	39.9	412.9
Total Benzene Reduction[f] (Mg/Year)	----	9.9	12.7	13.5	15.7	----	25.4	32.6	34.6	40.1	----	58.9	75.9	80.6	93.1
Cost-Effectiveness[g] (Net Annualized $1,000/Mg Benzene)	----	0.30	0.46	0.89	5.3	----	0.0	0.17	0.74	6.2	----	0.0	0.10	0.50	4.4

[a] From Table 8-4.

[b] From Table 8-11.

[c] From Table 8-9 - Recovered product credit is based on VOC emission reductions from the baseline Alternative I.

[d] Numbers in parentheses represent savings.

[e] Net annualized cost is calculated as the difference between the total annualized cost (Table 8-11) and the recovered product credit (Table 8-9) for each model unit and regulatory alternative.

[f] From Table 8-12.

[g] Calculated by dividing the net annualized cost ($1000) by the total benzene reduction for each model unit and regulatory alternative

Units B and C, respectively, are estimated. For Regulatory Alternative III, emissions are expected to decrease 68, 73, and 78 percent for Model Units A, B, and C, respectively. Reductions of 73, 77, and 83 percent are estimated for Model Units A, B, and C, respectively, for Regulatory Alternative IV. Regulatory Alternative V, the most stringent control level, is estimated to reduce emissions from the baseline level by 84 percent for Model A, 90 percent for Model B, and 96 percent for Model C. For existing units, the annualized cost-effectiveness varies from no cost (Models B and C, Regulatory Alternative II) to $9,100/Mg of benzene (Model B, Regulatory Alternative V). For new units, the cost-effectiveness ranges from no cost (Models B and C, Regulatory Alternative II) to $6,200/Mg benzene (Model B, Regulatory Alternative V).

8.4 TOTAL INDUSTRY IMPACTS

The total nationwide estimated costs, recovered product credits, and benzene fugitive emissions for the refining and organic chemical industries are presented in Table 8-15 for existing units and in Table 8-16 for new units.

8.4.1 Existing Units

For existing sources, which are estimated at 241 production units, economic impacts range from a capital cost of $2.9 million for Regulatory Alternative II to a capital cost of $242 million for Regulatory Alternative V, based on second quarter 1979 dollars. These costs result in annualized costs ranging from a net savings of $25,000 for Regulatory Alternative II to an annual cost of $58.6 million for Regulatory Alternative V. The alternatives would result in nationwide benzene fugitive emissions ranging from 3,600 Mg/yr for Regulatory Alternative II to 900 Mg/yr for Regulatory Alternative V. These rates compare with an uncontrolled rate of 8,300 Mg/yr for Regulatory Alternative I. The resulting cost-effectiveness of the regulatory alternatives ranges from a savings of $10/Mg for Regulatory Alternative II to a cost of $7,900/Mg for Regulatory Alternative V.

8.4.2 New Units

The costs and estimates in Table 8-16 represent fifth-year estimates based on the number of new model units predicted to be operating in 1985. Fifth-year impacts for an estimated 68 production units ranged

Table 8-15. NATIONWIDE COSTS FOR THE
EXISTING INDUSTRY
(May 1979 Dollars)[a]

	REGULATORY ALTERNATIVE				
	I	II	III	IV	V
Total Capital Cost ($ Million)	0.0	2.9	9.7	25.3	242
Total **Annualized Cost** ($ Million)	0.0	2.2	4.9	8.5	62.0
Total Annual Credit ($ Million)	0.0	(2.3)[b]	(2.8)[b]	(3.0)[b]	(3.4)[b]
Net **Annualized Cost** ($ Million)	0.0	(0.03)[b]	2.1	5.5	58.6
Total Benzene Fugitive Emissions[c] (1000 Mg/yr)	8.3	3.6	2.2	1.9	0.9
Total Benzene Fugitive Emission Reduction (1000 Mg/yr)	---	4.7	6.0	6.4	7.4
Cost-Effectiveness Net Annual Cost, $1000/ Mg Benzene Reduced	---	0.0	0.4	0.9	7.9

---

[a] Calculated by multiplying cost and emission estimates for each model unit and regulatory alternative (from Table 8-13) by the following numbers of existing model units:

Model Unit	Number of Existing Units in 1980
A	145
B	72
C	24

[b] Numbers in parentheses represent savings.

[c] From Table 8-12, calculated by multiplying emissions for each model unit and regulatory alternative by the number of existing model units in footnote a.

Table 8-16. NATIONWIDE COSTS FOR
NEW UNITS (FIFTH YEAR IMPACT)[a]

	REGULATORY ALTERNATIVE				
	I	II	III	IV	V
Total Capital Cost ($ Million)	0.0	0.8	2.2	6.5	48.4
Total Annualized Cost ($ Million)	0.0	0.6	1.2	2.2	12.4
Total Annual Credit ($ Million)	0.0	(0.7)[b]	(0.8)[b]	(0.9)[b]	(1.0)[b]
Net Annualized Cost ($ Million)	0.0	(0.07)[b]	0.4	1.3	11.4
Total Benzene Fugitive Emissions[c] (1000 Mg/yr)	2.5	1.1	0.7	0.5	0.2
Total Benzene Fugitive Emission Reduction (1000 Mg/yr)	---	1.5	1.9	2.0	2.3
Cost-Effectiveness (Net Annual Cost, $1000/ Mg Benzene Reduced	---	0.0	0.2	0.7	5.0

[a] Calculated by multiplying cost and emission estimates for each model unit and regulatory alternative (from Table 8-14) by the following numbers of new model units predicted to be in operation in 1985:

Model Unit	Number of New Units in 1985
A	47
B	7
C	14

[b] Numbers in parentheses represent savings.

[c] From Table 8-12, calculated by multiplying emissions for each model unit and regulatory alternative by the number of new model units in footnote a.

from a capital cost of $820 thousand for Regulatory Alternative II to a capital cost of $48.4 million for Regulatory Alternative V, based on second quarter 1979 dollars. These costs would result in annualized costs ranging from a net savings of $70,000 for Regulatory Alternative II to an annual cost of $11.4 million for Regulatory Alternative V. The alternatives would result in nationwide benzene fugitive emissions ranging from 1,100 Mg/yr for Regulatory Alternative II to 200 Mg/yr for Regulatory Alternative V. These rates compare with an uncontrolled rate of 2,500 Mg/yr for Regulatory Alternative I. The resulting cost-effectiveness for new sources ranges from a savings of $50/Mg for Regulatory Alternative II to a cost of $5,000/Mg for Regulatory Alternative V.

8.5 COST COMPARISON

The costs of controlling benzene fugitive emissions from the refining and organic chemical industries are compared with other benzene source categories in order to consider the total impact of all regulations (e.g., OSHA, air and water quality, solid waste) on the entire benzene industry. Control cost data for comparison with the benzene fugitive sources are derived from capital and annual control cost estimates that are presented in the proposed NESHAP documents for the above source categories.[10-12] Table 8-17 summarizes capital and annual control cost data for benzene fugitive emissions from the refining and organic chemical industries, the maleic anhydride and ethylbenzene-styrene industries (process emissions), and benzene storage tanks from consumers and producers. In each category, ranges of control costs are given for existing and/or new units, reflecting differences in model units and control technologies. In general, the range of capital and annualized costs for the benzene fugitive sources (refining and organic chemical industries) is much wider than the range for the other sources. Control costs for the maleic anhydride plants (existing) appear to be the highest, followed by costs for controlling benzene fugitive sources.

Tables 8-18 and 8-19 present total control costs associated with all emissions (i.e., process, fugitive, and storage) for existing and new units representative of the maleic anhydride and ethylbenzene-styrene

Table 8-17. RANGE OF CONTROL COSTS FOR THE BENZENE SOURCE CATEGORIES FOR EXISTING AND NEW UNITS

(Thousands of Dollars)

	Total Capital Cost		Total Annual Cost[a]	
Source Category	Existing	New	Existing	New
Refinery-organic chemical (Benzene Fugitives)	10-2502	10-1754	(11)-609	(13)-413
Maleic Anhydride[10] (Process Emissions)	1160-1440	----	354-600	----
Ethylbenzene-Styrene[11] (Process Emissions)	268-555	----	(150)-45	----
Benzene Storage[12] (Producers)	7-290	6-290	0.2-68	0-69
Benzene Storage[12] (Consumers)	16-249	15-249	2-68	(0.8)-62[b]

[a] Includes recovered credits.

[b] Numbers in parentheses represent savings.

Table 8-18. COSTS FOR THE CONTROL OF TOTAL BENZENE EMISSIONS FROM THE MAELIC ANHYDRIDE INDUSTRY[10,12,a]

(Thousands of Dollars)

Cost Item	Existing	New
Capital Cost	1193-3018	31-1241
Annual Cost[b]	359-725	4-54

[a] Includes control costs for benzene fugitive emissions from refineries and chemical plants.

[b] Includes recovered credits.

Table 8-19. COSTS FOR THE CONTROL OF TOTAL BENZENE EMISSIONS FROM THE ETHYLBENZENE-STYRENE INDUSTRY[11,12,a]

(Thousands of Dollars)

Cost Item	Existing	New
Capital Cost	301-2133	31-1241
Annual Cost[b]	(150)-114	4-54

[a] Includes control costs for benzene fugitive emissions from refineries and chemical plants.

[b] Includes recovered credits.

[c] Number in parentheses represents savings.

industries, respectively. Total control cost data are given in Table 8-20 for controlling benzene emissions from producer storage tanks and fugitive sources, while similar costs are incurred for benzene emission controls from consumer storage tanks and fugitive sources, as shown in Table 8-21.

Table 8-20. TOTAL COSTS FOR THE CONTROL OF BENZENE EMISSIONS FROM PRODUCER BENZENE STORAGE TANKS AND BENZENE FUGITIVE SOURCES[12,a]

(Thousands of Dollars)

Cost Item	Existing	New
Capital Cost	17-2792	16-2044
Annual Cost[b]	(11)-677	(13)-482

[a] Includes control costs for benzene fugitive emissions from refineries and chemical plants.

[b] Includes recovered credits.

[c] Numbers in parentheses represent savings.

Table 8-21. TOTAL COSTS FOR THE CONTROL OF BENZENE EMISSIONS FROM CONSUMER BENZENE STORAGE TANKS AND BENZENE FUGITIVE SOURCES[12,a]

(Thousands of Dollars)

Cost Item	Existing	New
Capital Cost	26-2751	25-2003
Annual Cost[b]	(9)-677	(14)-475

[a] Includes control costs for benzene fugitive emissions from refineries and chemical plants.

[b] Includes recovered credits.

[c] Numbers in parentheses represent savings.

8.6 REFERENCES

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9.0 ECONOMIC IMPACT

9.1 INDUSTRY CHARACTERIZATION

9.1.1 General Profile

Throughout the United States there are 74 petroleum refining and organic chemical companies operating 131 plant sites that manufacture benzene and derivatives of benzene.[1-15,32-33] Table 9-1 lists the companies alphabetically and shows their plant locations and capacities as obtained from the most recent data available. In addition, the table includes 6 new plants under construction of 1 or more units, 14 existing plants undergoing expansion, 6 on standby or not currently in operation, and 1 plant in the engineering phase of construction.

Table 9-1 lists 32 companies that currently produce pure benzene at 50 plant sites by 74 units (e.g., Sulfolane, UDEX). Benzene is also produced as an impure by-product in the manufacture of ethylene, which is produced by 28 companies at 46 sites and 58 units. There are 50 companies that manufacture benzene derivatives at 76 production sites. These derivatives, which consume benzene as a feedstock, are listed in Table 9-2.

Benzene, ethylene, and benzene-derivative production is fairly concentrated geographically. Over 85 percent of the total U.S. benzene capacity is located in two states and one territory: Texas (61 percent), Louisiana (19 percent), and Puerto Rico (7 percent).

9.1.2 Production of Benzene, Ethylene, and Benzene Derivatives

Total 1977 U.S. production of benzene by petroleum refining and organic chemical production units was estimated to be 5260 gigagrams (Gg).[16,26] Total ethylene production was higher at 10,600 Gg, while total production of benzene derivatives was approximately 8700 Gg. Table 9-3 summarizes 1977 production and capacity data for benzene, ethylene, and benzene derivatives.

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL[1-15,32-33]

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
1. Allied Chemical	Geismar, LA	Et	340
2. Allied Chemical	Moundsville, WV	NiBz	25
3. American Cyanamid	Bound Brook, NJ	NiBz	48
4. American Cyanamid	Willow Island, WV	NiBz[c]	34
5. Amerada Hess	St. Croix, VI	Bz	217
6. American Hoechst	Baton Rouge, LA	EtBz	526
		St	ND[g]
7. American Hoechst	Bayport, TX	EtBz[d]	469
		St[d]	409
8. American Petrofina (of Texas)	Port Arthur, TX	Bz	67
9. American Petrofina (Cosden Oil)	Big Spring, TX	Bz	194
		Cyx	35
		EtBz[e]	20
		St	41
10. American Petrofina (Cosden Oil/Petrogas)	Groves, TX	Et	9
11. American Petrofina/ Union Oil of CA	Beaumont, TX	Bz	73
		Cyx	88
12. Ashland Oil	Ashland, KY	Bz	214
		Cu	181
		Cyx	ND[g]
13. Ashland Oil	Neal, WV	MAN	27
14. Ashland Oil	North Tonawanda, NY	Bz	77
15. Atlantic Richfield	Beaver Valley, PA (Kobuta)	St	200
16. Atlantic Richfield	Channelview, TX	Bz[c]	107
		Et (2 units)	1179

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONTINUED)

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
17. Atlantic Richfield	Wilmington, CA	Bz	40
		Et	45
18. Atlantic Richfield (ARCO/Polymers)	Houston, TX	Bz[c]	140
		Et	227
		EtBz	61
		St	54
19. Atlantic Richfield (ARCO/Polymers)	Port Arthur, TX	EtBz	114
20. Charter International	Houston, TX	Bz	17
		EtBz	16
21. Chemetics International	Geismar, LA	NiBz	173
22. Chemplex	Clinton, IO	Et	227
23. Cities Service	Lake Charles, LA	Bz	83
		Et (2 units)	400
24. Clark Oil	Blue Island, IL	Cu	50
25. Coastal States Gas	Corpus Christi, TX	Bz	234
		Cu[e]	64
26. Commonwealth Oil	Penuelas, PR	Bz	618
		Cyx	117
		EtBz[e]	73
27. Continental Oil	Baltimore, MD	LAB	122
28. Continental Oil	Lake Charles, LA	Et	302
29. Core-Lube	Danville, IL	BSA	ND[g]
30. Corpus Christi Petrochemicals	Corpus Christi, TX	Bz[d]	100
		Et[d]	544
31. Cos-Mar, Inc.	Carrville, LA	EtBz	690
		St	590
32. Crown Central	Pasadena, TX	Bz	77
33. Denka (Petrotex)	Houston, TX	MAN	23
34. Dow Chemical	Bay City, MI	Bz	100
		Et	86

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONTINUED)

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
35. Dow Chemical	Freeport, TX	Bz	167
		Et (5 units)	1136
		EtBz	794
		St	658
36. Dow Chemical	Midland, MI	ClBz	129
		EtBz[e]	249
		St	181
37. Dow Chemical	Orange, TX	Et	375
38. Dow Chemical	Plaquemine, LA	Bz[d]	200
		Et (2 units)	545
39. Dupont	Beaumont, TX	NiBz	159
40. Dupont	Gibbstown, NJ	NiBz	110
41. Dupont	Orange, TX	Et	374
42. Eastman Kodak	Longview, TX	Et	580
43. El Paso Natural Gas	Odessa, TX	Et	ND[g]
		EtBz	125
		St	68
44. El Paso Products/ Rexene Polyolefins	Odessa, TX	Et	236
		St[c]	47
45. Exxon	Baton Rouge, LA	Bz	234
		Et	816
		EtBz	ND[g]
		St	ND[g]
46. Exxon	Baytown, TX	Bz	200
		Cyx	147
		Etc	36
47. First Chemical	Pascagoula, MS	NiBz	152
48. Georgia-Pacific	Houston, TX	Cu	340
49. Getty Oil	Delaware City, DE	Bz	37

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONTINUED)

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
50. Getty Oil	El Dorado, KA	Bz	43
		Cu	61
51. B.F. Goodrich	Calvert City, KY	Et	136
52. Goodyear Tire & Rubber	Bayport, TX	Hqn	5
53. Gulf Coast Olefins	Taft, LA	Et[c]	218
54. Gulf Oil	Alliance, LA	Bz	224
55. Gulf Oil	Donaldsonville, LA	EtBz	313
		St	272
56. Gulf Oil	Philadelphia, PA	Bz	124
		Cu	209
57. Gulf Oil Chemicals	Cedar Bayou, TX	Et (2 units)	719
58. Gulf Oil Chemicals	Port Arthur, TX	Bz[c]	134
		Cu	204
		Cyx	106
		Et (2 units)	558
59. Hercules	McGregor, TX	ClBz[f]	0.05
60. Howell	San Antonio, TX	Bz	ND[g]
61. ICC Industries	Niagara Falls, NY	ClBz	11
62. Independent Refining Corp.	Winnie, TX	Bz	10
63. Jim Walter Resources	Birmingham, AL	BSA	ND[g]
64. Kerr-McGee Corp.	Corpus Christi, TX	Bz	53
65. Koppers	Bridgeville, PA	MAN	15
66. Koppers	Cicero, IL	MAN	5
67. Koppers	Petrolia, PA	Rcnol	16
68. Marathon Oil	Texas City, TX	Bz	23
		Cu[e]	95
69. Mobay Chemical	New Martinsville, WV	NiBz	61

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONTINUED)

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
70. Mobil Oil	Beaumont, TX	Bz	200
		Et	410
71. Monsanto	Alvin, TX (Chocolate Bayou)	Cu	340
		Et[c]	285
		EtBz	27
		LAB	102
72. Monsanto	Sauget, IL	ClBz	80
		NiBz	5
73. Monsanto	St. Louis, MO	MAN	48
74. Monsanto	Texas City, TX	Bz	284
		Et	45
		EtBz	744
		St	680
75. Montrose Chemical	Henderson, NV	ClBz	32
76. National Distillers (U.S.I.)	Tuscola, IL	Et	181
77. Nease Chemical	State College, PA	BSA[e]	ND[g]
78. Northern Petrochemical	Morris, IL	Et	400
79. Olin Corporation	Brandenburg, KY	Et	50
80. Oxirane	Channelview, TX	EtBz	525
		St	454
81. Pennzoil (Atlas)	Shreveport, LA	Bz[c]	49
82. Phillips Petroleum	Borger, TX	Cyx	104
		EtBz	ND[g]
83. Phillips Petroleum	Pasadena, TX	Et	13
84. Phillips Petroleum	Sweeny, TX	Bz	33
		Cyx	250
		Et (3 units)	973

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONTINUED)

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
85. Phillips Puerto Rico	Guayama, PR	Bz	367
		Cyx[c]	212
86. Puerto Rico Olefins	Penuelas, PR	Et	454
87. PPG	Natrium, WV	ClBz	ND[g]
88. PPG	New Martinsville, WV	ClBz	64
89. Quintana-Howell	Corpus Christi, TX	Bz[c]	23
90. Reichhold Chemicals	Elizabeth, NJ	MAN	14
91. Reichhold Chemicals	Morris, IL	MAN	20
92. Reichhold Chemicals	Tuscaloosa, AL	BSA	ND[g]
93. Rubicon	Geismar, LA	NiBz	170
94. Shell Chemical	Houston, TX	Et	590
95. Shell Oil	Deer Park, TX	Bz[c]	301
		Cu	326
		Et	681
96. Shell Chemical	Norco, LA	Bz[d]	133
		Et[d]	681
97. Shell Oil	Odessa, TX	Bz	40
98. Shell Oil	Wood River, IL	Bz	150
99. Specialty Organics	Irwindale, CA	ClBz	2
100. Standard Chlorine	Delaware City, DE	ClBz	125
101. Standard Chlorine	Kearny, NJ	ClBz	7
102. Standard Oil (CA)/ Chevron Chemical	El Segundo, CA	Bz	77
		Cu	45
103. Standard Oil (CA) Chevron	Pascagoula, MS	Bz	ND[g]
104. Standard Oil (CA) Chevron	Richmond, CA	Bz	ND[g]
105. Standard Oil (IN)/ Amoco	Alvin, TX	Et (2 units)	907

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONTINUED)

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
106. Standard Oil (IN)/ Amoco	Texas City, TX	Bz	284
		Cu	14
		EtBz	386
		St	381
107. Standard Oil (OH)/ BP Oil	Marcus Hook, PA	Bz	27
108. Stauffer Chemical	Henderson, NV	BSA	4
109. Sun Oil	Corpus Christi, TX	Bz	127
		Cu	113
		Et	9
		EtBz	61
		St	54
110. Sun Oil	Marcus Hook, PA	Bz	97
111. Sun Oil	Toledo, OH	Bz[c]	164
112. Sun Oil	Tulsa, OK	Bz	80
		Cyx[c]	83
113. Sun-Olin	Claymont, DE	Et	109
114. Tenneco	Chalmette, LA	Bz	33
		EtBz	16
115. Tenneco	Fords, NJ	MAN	12
116. Texaco	Port Arthur, TX	Bz	150
		Cyx[c]	117
		Et	454
117. Texaco	Westville, NJ	Bz	117
		Cu	64
118. Texaco/Jefferson Chemical	Bellaire, TX	Et	240
119. Texaco/Jefferson Chemical	Port Neches, TX	Et	238

Table 9-1. REFINERIES AND ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONTINUED)

Plant	City/State	Benzene-Related Products At Site[a]	Capacity[b] (Gg/yr)
120. Union Carbide	Institute, WV	EtBz	ND[g]
		LAB	64
		St	ND[g]
121. Union Carbide	Penuelas, PR	Bz	ND[g]
		Cu	290
		Et	454
122. Union Carbide	Seadrift, TX	Et	546
		EtBz	154
		St	136
123. Union Carbide	Taft, LA	Bz[c]	234
		Et	500
124. Union Carbide	Texas City, TX	Et	546
125. Union Carbide	Torrance, CA	Et	73
126. Union Oil of CA	Lemont, IL	Bz	57
127. Union Pacific/ Champlin	Corpus Christi, TX	Bz	33
		Cu[d]	ND[g]
		Cyx	65
128. U.S. Steel	Neville Island, PA	MAN	38
129. USS Chemicals	Houston, TX	Et	227
130. Vertac/Transvaal	Jacksonville, AR	ClBz	ND[g]
131. Witco Chemical	Carson, CA	LAB	20

[a] BSA = Benzenesulfonic Acid
Bz = Benzene
ClBz = Chlorobenzene
Cu = Cumene
Cyx = Cyclohexane
Et = Ethylene
EtBz = Ethylbenzene
Hqn = Hydroquinone
LAB = Linear Alkylbenzene
MAN = Maleic Anhydride
NiBz = Nitrobenzene
Rcnol = Resorcinol
St = Styrene

Table 9-1. REFINERIES AND SYNTHETIC ORGANIC CHEMICAL MANUFACTURING SITES WITH BENZENE FUGITIVE EMISSION POTENTIAL (CONCLUDED)

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[b] Annual capacities for each product were obtained from the following sources (effective date of capacity in parentheses):

BSA - Ref. 3 (January 1977)
Bz - Refs. 3 (January 1977), 14
ClBz - Refs. 4 (January 1977), 13, 14
Cu - Ref. 9 (January 1979), 13, 14
Cyx - Ref. 2 (November 1976), 3 (January 1977)
Et - Refs. 5 (1977 year-end), 15 (June 1979), 11, 13, 14, 33
EtBz - Ref. 10 (January 1979)
Hqn - Capacity estimate from industry (1979)
LAB - Ref. 8 (June 1978)
MAN - Ref. 3 (January 1977)
NiBz - Refs. 7, 32
Rcnol - Ref. 6
St - Refs. 1 (1977 year-end), 14

[c] Product unit under expansion

[d] Product unit under construction

[e] Product unit on standby or not currently in use

[f] Product unit in engineering phase

[g] No data available

Table 9-2. NUMBER OF COMPANIES AND PLANT SITES THAT MANUFACTURE BENZENE DERIVATIVES

Benzene Derivative	Number of Companies	Number of Sites (and Units)
Chlorobenzene	8	10
Nitrobenzene	8	10
Ethylbenzene	15	18
Styrene	10	14
Linear Alkylbenzene	4	4
Cyclohexane	9	11
Cumene	12	13
Maleic Anhydride	8	10
Resorcinol	1	1
Benzenesulfonic Acid	4	4
Hydroquinone	1	1

9.1.3 Methods of Manufacture

9.1.3.1 Benzene. Benzene is primarily manufactured by five methods. In most instances, benzene producers obtain the material from which benzene is made from their own refining or manufacturing operations. In other cases, a benzene producer may buy benzene-containing material from another source. Four of the methods (extraction from catalytic reformate, toluene dealkylation, toluene disproportionation, and processing benzene from pyrolysis gasoline) use refinery products as the feedstock; coke-oven light oil, from which benzene can also be extracted, is a by-product of converting coal into coke for steel manufacturing. Of these methods, extraction from catalytic reformate accounted for over half of the 1976 benzene supply.

9.1.3.2 Ethylene. Almost all commercial ethylene is produced by pyrolysis of natural-gas liquids and petroleum fractions. Although significant amounts of ethylene were once extracted from by-product refinery streams (40 percent of the U.S. production in 1956), only

Table 9-3. SUMMARY OF PRODUCTION AND CAPACITY FOR BENZENE, ETHYLENE, AND BENZENE DERIVATIVES[1-10]

Product	Total U.S. Capacity (Gg 1977)	Total U.S. Production (Gg 1977)	Capacity Utilization
Benzene	7,008	5,256[a]	75 Percent
Ethylene	15,100	10,600	70 Percent
Chlorobenzenes	440	234	53 Percent
Nitrobenzene	441	252	61 Percent
Ethylbenzene	5,070	2,829	56 Percent
Styrene	3,741	2,694[a]	72 Percent
Linear Alkylbenzenes	308	239	78 Percent
Cyclohexane	1,395	983	70 Percent
Cumene	1,653	1,281	77 Percent
Maleic Anhydride	236	132	56 Percent
Resorcinol	16[b]	14[a]	86 Percent[c]
Benzenesulfonic Acid	61[b]	48[b]	79 Percent[b]
Hydroquinone	3[b]	N.D.[d]	N.D.[d]

[a] Estimated from the percent capacity utilization for the product.

[b] Represents 1977 capacity for one company.

[c] Based on benzene consumption estimated for 1976.

[d] N.D. designates no data available.

about 2 percent of the current ethylene production is derived from this source. Most of the plants that are extracting ethylene from refinery streams also produce ethylene by pyrolysis.[17]

Several alternative pyrolysis processes, primarily utilizing feedstocks not currently in common use, are either being commercially attempted on a limited scale or are in the developmental stage with expectations of limited commercial application between 1980 and 1985. Although these processes are all expected to be commercially proven within five years, wide application will depend on demonstrated favorable process economics. No significant impact on total olefins production is anticipated from these developmental processes for at least 10 years.[17]

The primary difference between the domestic and foreign olefins industries has been in the feedstocks used for pyrolysis. In Japan and Europe natural-gas liquids have historically been scarce and naphtha has been the predominant feedstock.[17]

9.1.3.3 Chlorobenzene. All domestic chlorobenzene production is based on direct chlorination of benzene. The principal chlorobenzene product is monochlorobenzene with smaller amounts of ortho- and para-dichlorobenzene being co-produced.[18]

9.1.3.4 Nitrobenzene. Nitrobenzene is produced by the direct nitration of benzene with a mixture of nitric acid, sulfuric acid, and water.[19,20] The reaction vessels are specially built cast iron or steel kettles fitted with efficient agitators. The kettles are jacketed and generally contain internal cooling coils for proper temperature control of the strongly exothermic reaction. Typically, a batch process is employed; however, newer plants use a continuous process.

9.1.3.5 Ethylbenzene/Styrene. More than 95 percent of domestic ethylbenzene production is by benzene alkylation with ethylene. The remainder is recovered by distillation from mixed xylene streams that result from naphtha reforming or cracking in petroleum refineries. More than 99 percent of the ethylbenzene produced is used as an intermediate for making styrene, often in an integrated ethylbenzene-styrene plant. Except for a new plant brought on-stream in July 1977 by

Oxirane Corporation, all domestic styrene is produced by catalytic dehydrogenation of ethylbenzene. The Oxirane ethylbenzene oxidation process is also used in Spain and Japan; however, most foreign styrene production is by dehydrogenation of ethylbenzene.[21]

9.1.3.6 Linear Alkylbenzene. Two major processes are used to manufacture linear alkylbenzene (LAB) in the United States. Approximately 67 percent is manufactured by three companies using the paraffin chlorination process, and approximately 33 percent is manufactured by one company using the olefin (paraffin dehydrogenation) process. The only significant foreign process not used in the United States uses as feedstock the linear alpha olefins produced by Shell's wax cracking process (Shell Nederland Chemie NV, Pernis, The Netherlands). These linear alpha olefins are alkylated with benzene at several locations to produce LAB, but the LAB from linear alpha olefins produces a detergent with a slightly different balance of detergent properties.[22]

9.1.3.7 Cyclohexane. Two processes are used commercially to manufacture cyclohexane: catalytic hydrogenation of benzene, which accounts for approximately 85 percent of the cyclohexane capacity in the United States; and separation from petroleum liquids, which constitutes the remaining 15 percent.[23]

9.1.3.8 Maleic Anhydride. The two major processes used to manufacture maleic anhydride (MAN) in the United States are benzene oxidation and butane oxidation. Most major U.S. producers are employing the first method. A small amount of MAN is recovered as a by-product of phthalic anhydride production. The only significant foreign process for MAN production not used in the United States starts with a butene mixture feedstock. This process is operated in France and Japan.[24]

9.1.3.9 Cumene. All commercial cumene is produced by alkylating benzene in the vapor phase with propylene in the presence of a phosphoric acid catalyst. An excess of benzene is maintained to suppress dialkylation, oligomerization, and other side reactions.[20] Essentially all cumene produced is consumed in the manufacture of phenol and acetone.[9]

9.1.3.10 Resorcinol. All commercial resorcinol is produced by the benzene sulfonation process, in which benzene is sulfonated to m-disulfonic acid and treated with sodium sulfite to form sodium salt. After the salt is fused with sodium hydroxide, dissolved in water, and acidified with sulfuric acid, resorcinol is obtained by solvent extraction. Other processes have been developed, but such operations have not been proved commercially successful.[6]

9.1.3.11 Benzenesulfonic Acid (BSA). BSA can be produced by three methods: sulfonation with sulfuric acid, oleum, or sulfur trioxide.[20] Sulfonation with sulfuric acid can be accomplished by a batch or continuous process. In the batch process, benzene and sulfuric acid monohydrate are added to a sulfonator, agitated, and heated. In the continuous process, sulfuric acid is steadily fed to the sulfonator simultaneously with benzene, which has been previously fed through a vaporizer-superheater. The mixture flows through the reactor and is discharged from the bottom.

Sulfonation with oleum is accomplished by charging liquid benzene to a pre-sulfonator and feeding 9.5 percent oleum over a period of time. The mixture is pumped to vapor-feed sulfonators where benzene vapor is added until a desired residual-acid level is attained. The BSA mixture flows from the bottom of the reactor to storage.

In the third sulfonation method, benzene reacts with sulfur trioxide in liquid sulfur dioxide, which is evaporated until a certain temperature is attained. Benzene is then added, the temperature is raised, and sulfur dioxide is removed by an air stream.

9.1.3.12 Hydroquinone. In the manufacture of hydroquinone, benzene (or recycled cumene) is alkylated with propylene to yield four intermediate products: p-diisopropylbenzene (p-DIPB), o-DIPB, m-DIPB, and triisopropylbenzene (TIPB). The p-DIPB is purified and oxidized to a dihydroperoxide. Addition of sulfuric acid effectively splits the intermediate into hydroquinone and acetone. The other intermediates are reacted with benzene to yield cumene, which is recycled back to the alkylation process.[25] This method is used by the only U.S. producer of hydroquinone.

Hydroquinone can also be manufactured by oxidizing aniline to form p-benzoquinone, which is reduced, filtered to remove iron oxide, and distilled. The distilled product is dissolved in dilute sulfuric acid with a decolorizing agent and then filtered. A small amount of sodium hydrosulfite is added to the filtrate from which the hydroquinone crystallizes.[20]

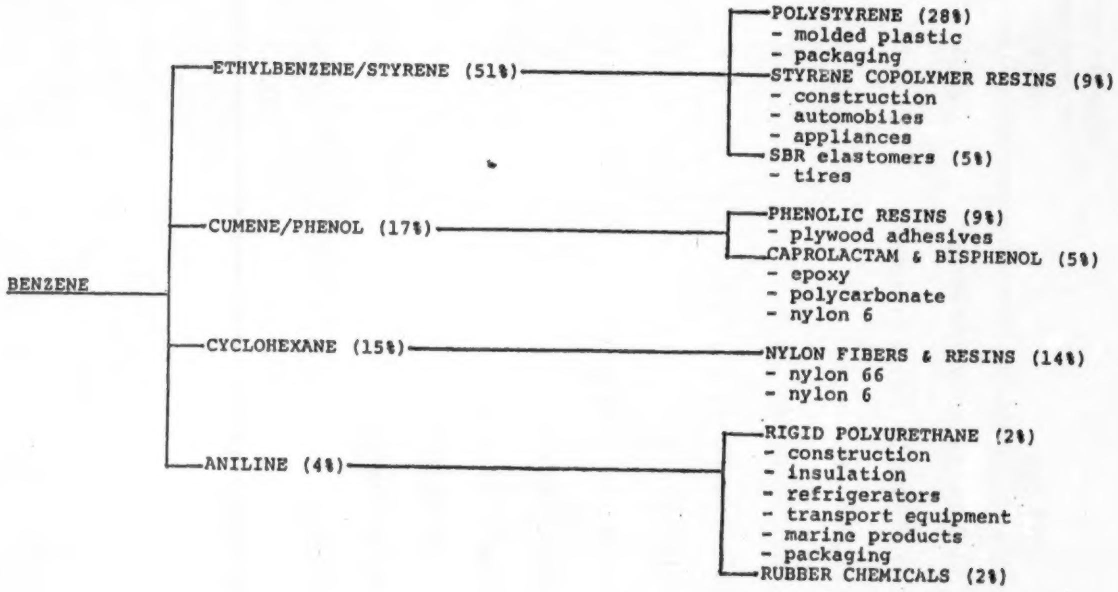
9.1.4 Uses of Benzene

The companies that produce benzene often consume it in the manufacture of another product. According to the International Trade Commission, captive consumption accounted for 55 percent of production in 1976 and 54 percent of production in 1977.[26] Captive consumption is relatively dependent on benzene price, since the prices of products made from benzene usually follow the same trends as benzene prices.

As a feedstock material, benzene presents a complex picture because of the diverse number of chemicals derived from it. Benzene derivatives find their largest uses in consumer goods, which account for 25 percent of the benzene produced in the U.S. This area comprises packaging, toys, sporting goods, disposables, novelties, and other small items. The major benzene derivatives used for these products include styrenics such as polystyrene, epoxy resins, acrylonitrile-butadiene-styrene (ABS) and styrene acrylonitrile (SAN). The other major end-uses are household goods and transportation, each taking 17 percent of the benzene consumption. Household goods — furniture, appliances, carpeting — use nylon fibers and resins, ABS, polystyrene, phenolics, and epoxies, among others. Plastics, fibers, elastomers, and rubber are used in boats and airplanes, as well as in trucks and automobiles.[27]

Figure 9-1 depicts the usage and percentages of total benzene production that is consumed by intermediate and final products. The products that demand over half of the benzene production are ethylbenzene and styrene. Tables 9-4 through 9-17 list the usage of ethylene and benzene derivatives. As shown in the tables, some of these products are consumed almost entirely (often captively) as intermediates in the manufacture of another product. In such cases, the use and consumption of the second-generation product have been included for reference.

Figure 9-1. Percentages of Total Benzene Production Consumed by Intermediate and Final Products (1976)*[3]


BENZENE
ETHYLBENZENE/STYRENE (51%)
CUMENE/PHENOL (17%)
CYCLOHEXANE (15%)
ANILINE (4%)
POLYSTYRENE (28%)
- molded plastic
- packaging
STYRENE COPOLYMER RESINS (9%)
- construction
- automobiles
- appliances
SBR elastomers (5%)
- tires
PHENOLIC RESINS (9%)
- plywood adhesives
CAPROLACTAM & BISPHENOL (5%)
- epoxy
- polycarbonate
- nylon 6
NYLON FIBERS & RESINS (14%)
- nylon 66
- nylon 6
RIGID POLYURETHANE (2%)
- construction
- insulation
- refrigerators
- transport equipment
- marine products
- packaging
RUBBER CHEMICALS (2%)

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*Percentages are from 1976 data for benzene apparent consumption.

Table 9-4. ETHYLENE USAGE[17]

End Use	Percent of Consumption (1976)
Low-Density Polyethylene	27.4
High-Density Polyethylene	14.7
Ethylene Oxide	18.6
Vinyl Chloride	12.0
Ethylebenzene, Styrene	9.1
Ethyl Alcohol	3.5
Aliphatic Alcohols	2.5
Acetaldehyde	2.6
Vinyl Acetate	2.2
Ethyl Chloride	1.4
Alpha Olefins	1.5
Other	4.5
	100.0

Table 9-5. MONOCHLOROBENZENE USAGE[18]

End Use	Percent of Consumption (1977)
Solvents	30
Nitrochlorobenzene (Agricultural Products)	35
DDT, Silicones, etc.	15
Diphenyl Oxide	10
Rubber Intermediates	10

Table 9-6. DICHLOROBENZENES USAGE[18]

End Use	Percent of Consumption (1976)
o-Dichlorobenzene	
3,4,Dichloroaniline, etc.	65
TDI* Process Solvent	15
Solvents	10
Dye Manufacture	5
Pesticides, etc.	5
p-Dichlorobenzene	
Space Deodorant	90
Intermediate for Pesticides	10

*Toluene Diisocyanate

Table 9-7. NITROBENZENE USAGE[7]

End Use	Percent of Consumption (1978)
Aniline	98
Solvent, Dichloroaniline	2

Table 9-8. ANILINE USAGE[7]

End Use	Percent of Consumption (1978)
MDI*	52
Rubber Chemicals	29
Dyes	4
Hydroquinone	3
Drugs, Pesticides	12

*p,p'-Methylene Diphenyldiisocyanate

Table 9-9. ETHYLBENZENE USAGE[20]

End Use	Percent of Consumption (1976)
Styrene	99
Solvent	1

Table 9-10. STYRENE USAGE[20]

End Use	Percent of Consumption (1976)
Polystyrene	54
Styrene Copolymer Resins	17
Styrene-Butadiene Elastomers	9
Unsaturated Polyester Resins	6
Miscellaneous	1
Exports	13

Table 9-11. LINEAR ALKYLBENZENE USAGE[8]

End Use	Percent of Consumption (1977)
Linear Alkylbenzene Sulfonates*	90
Export	10

*Detergent Surfactant.

Table 9-12. CYCLOHEXANE USAGE[22]

End Use	Percent of Consumption (1977)
Adipic Acid	53
Exports	18
Caprolactam	23
1,6,-Hexamethylenediamine (HMDA)	3
Miscellaneous	3

Table 9-13. CUMENE USAGE[9]

End Use	Percent of Consumption (1976)
Phenol and Acetone	99
α-Methylstyrene, Solvent	1

Table 9-14. MALEIC ANHYDRIDE USAGE[24]

End Use	Percent of Consumption (1975)
Unsaturated Polyester Resins	51.1
Fumaric Acid	6.4
Agricultural Chemicals	10.0
Alkyd Resins	1.3
Lubricating Additives	7.8
Copolymers	5.3
Reactive plasticizers	3.6
Maleic Acid	3.8
Chlorendic Anhydride and Acid	1.1
Surface-Active Agents	2.9
Other	6.7

Table 9-15. RESORCINOL USAGE[6]

End Use	Percent of Consumption (1977)
Rubber Products	59.6
Wood Adhesive Resins	25.5
Miscellaneous	14.9

Table 9-16. BENZENESULFONIC ACID USAGE[3]

End Use	Percent of Consumption
Phenol	N.D.*
Dyes	N.D.*

*N.D. designates no data available.

Table 9-17. HYDROQUINONE USACE[3]

End Use	Percent of Consumption
Rubber Antioxidant	N.D.*
Photographic Developer	N.D.*
Dye Intermediates	N.D.*

*N.D. designates no data available.

9.1.5 Price History

In spite of price controls through August 1976, benzene prices as well as benzene derivative prices rose at a greater rate than prices of most other chemicals in response to the higher cost of crude oil. Even with a decline in demand in 1975, benzene prices continued a general upward movement.[3] Table 9-18 gives the price history of benzene, ethylene, and benzene derivatives since 1974. Market experts forecast a continuing upward trend in benzene prices.[29] Increases in the cost of crude oil along with other market functions (discussed in Section 9.1.6 below) are responsible for a large portion of benzene price increases.

9.1.6 Market Factors that Affect the Benzene Industry.

Benzene is contained in materials that have other uses. Therefore, the chemical uses of benzene must be profitable enough to justify recovering benzene from these materials. Whether the benzene will be produced depends on a number of factors, such as the value of the material in which benzene is contained (reformate, pyrolysis gasoline, toluene, coke-oven light oil), the value of benzene before it is recovered, processing costs, operating costs, and the value of benzene in relation to benzene substitutes.

9.1.7 Feedstock Substitutions for Benzene Derivatives

The price of benzene has increased considerably since the beginning of 1979. As the cost of benzene rises, greater incentive is provided for developing and using alternative feedstocks for the production of benzene derivatives. For some products, such as nitrobenzene, there are no feedstock substitutes; consequently, increased benzene costs must be passed through to the customer. For other products, however, alternative processes using feedstocks other than benzene are available, and it is possible that production by such alternative processes will increase.

Table 9-19 lists some alternative processes by which benzene derivatives may be produced in the United States. Most of the substitute feedstocks used in these processes are derived from petroleum or natural gas, however, so that the economics of the alternative processes are still tied to the cost of crude oil and natural gas.

Table 9-18. PRICE HISTORY FOR BENZENE, ETHYLENE, AND BENZENE DERIVATIVES[28]

Product	Unit Price History (Dollars/Kilogram)					
	May 1979	1978	1977	1976	1975	1974
Benzene	0.37	0.22	0.24	0.23	0.23	0.23
Ethylene	0.31	0.29	0.27	0.25	0.19	0.17
Chlorobenzenes	0.30	0.27	0.27	N.D.[a]	0.29	0.25
Nitrobenzene	N.D.[a]	0.51	0.51	0.51	0.42	0.21
Aniline[b]	0.79	0.75	0.75	0.71	0.71	0.24
Ethylbenzene[c]	N.D.[a]	N.D.[a]	0.15	N.D.[a]	N.D.[a]	0.13
Styrene[d]	0.63	0.43	0.46	N.D.[a]	N.D.[a]	N.D.[a]
Linear Alkylbenzene	0.75	0.65	0.58	0.56	0.25	0.25
Cyclohexane	0.46	0.27	0.29	0.27	0.27	0.27
Cumene	0.40	0.31	0.31	0.31	0.35	N.D.[a]
Maleic Anhydride	0.88	0.68	0.82	0.82	0.82	0.35
Benzenesulfonic Acid/Phenol[e]	0.68	0.46	0.59	N.D.[a]	N.D.[a]	N.D.[a]
Resorcinol	3.09	2.87	2.72	N.D.[a]	N.D.[a]	N.D.[a]
Hydroquinone	3.39	3.39	3.30	N.D.[a]	N.D.[a]	N.D.[a]

[a] N.D. designates no data available.

[b] Since 97 to 98 percent of nitrobenzene production goes into aniline manufacture, aniline prices have been provided for comparison.

[c] Prices are not generally available for ethylbenzene because greater than 99 percent of production is captively consumed.

[d] Since most ethylbenzene production is consumed in styrene manufacture, styrene prices have been provided for comparison.

[e] Since benzenesulfonic acid (BSA) is used in the production of phenol and not as a final product, no price data are available for BSA. Prices given are for phenol.

Table 9-19. ALTERNATIVE PROCESSES FOR THE MANUFACTURE OF BENZENE DERIVATIVES

Benzene Derivative	Alternative Processes	Reference Number
Cumene	Separation from petroleum liquids	
Cyclohexane	Separation from petroleum liquids	2
Ethylbenzene	Extraction from mixed xylene streams	20
Maleic Anhydride	Oxidation of n-butane; by-product of phthalic anhydride production (xylene derivative)	3,20
Styrene	Propylene oxide coproduct; extraction from pyrolysis gasoline; production from toluene and ethylene via stilbene	1

9.1.8 Future Trends

9.1.8.1 Projected Growth Rates. Table 9-20 depicts projected growth rates for benzene, ethylene, and benzene derivatives through 1983. Demand for benzene produced from all sources (extraction from catalytic reformate, toluene dealkylation, toluene disproportionation, and processing benzene from pyrolysis gas) is expected to grow at 5 to 5.5 percent per year through 1985. The gap between production and capacity is expected to narrow from the 1977 value of 32 percent to about 20 percent by the end of this period.[27,29,30] Production capacity is expected to reach 8359 Gg by 1985.[27,31] During this forecast period, demand for benzene from catalytic reforming is likely to increase over 1977 requirements at about 1 percent annually, while toluene dealkylation production is expected to grow at approximately 3.4 percent per year. Benzene from pyrolysis gas extraction and dealkylation is expected to increase 14 percent per year, providing the largest new source of the aromatic.[27]

Styrene manufacture is expected to continue to be the biggest consumer of benzene, requiring over 50 percent of the benzene market, followed by cumene/phenol and cyclohexane. Benzene production capacity is expected to be satisfactory through 1982-83, with only minimal needs for additional capacity beyond this point until 1986-87.[27]

Table 9-20. PROJECTED ANNUAL GROWTH RATES FOR DEMAND OF BENZENE, ETHYLENE, AND BENZENE DERIVATIVES[1-10, 17-19, 21-24, 27]

Product	Projected Average Annual Percent Growth (1977 - 1983)
Benzene	5.5[a]
Ethylene	5.5
Chlorobenzenes	1.5
Nitrobenzenes	6.0
Ethylebenzene/Styrene	6.0
Linear Alkylbenzene	2.0
Cyclohexane	5.0
Cunene	7.5
Maleic Anhydride	11.0
Resorcinol	N.D.[b]
Benzenesulfonic Acid	N.D.[b]
Hydroquinone	N.D.[b]

[a] Growth rate for benzene is estimated at 5 to 5.5 percent per year through 1985.

[b] N.D. designates no data available.

Although capacity may pose no problem, benzene may grow scarce as the demand for unleaded gasoline increases into the early 1980's. Although the total demand for gasoline is growing slowly or not at all, the unleaded portion is increasing rapidly. With increased unleaded gas production, refiners need a higher clear-pool octane. The result is an increase in the amounts of aromatics needed in gasoline (see Section 9.1.6 above).[29,31]

9.1.8.2 Replacement Rate of Equipment. The replacement rate of benzene-manufacturing equipment is low since companies tend to refurbish their equipment on a continuous basis rather than replace it. This practice is characteristic of refining and organic chemical operations.

9.1.8.3 Planned Expansions of Capacity. Table 9-1 includes plants that are undergoing expansions of capacity through 1980. An additional capacity of 1119 Gg per year is estimated for all benzene-producing companies, 1407 Gg per year for all ethylene plants, and 1432 Gg per year for all plants that manufacture benzene derivatives.

Expansions of capacity will take place primarily at present plant locations by means of purchase or construction of new equipment. Capacity expansions are expected to be located mainly in Texas and Louisiana.

9.2 MICROECONOMIC IMPACT

9.2.1 Introduction

In the following sections the microeconomic impacts of applying the regulatory alternatives are detailed. Such impacts are discussed in terms of both the potential price, as well as capital availability, impacts of each alternative.

With regard to the maximum price increases, Regulatory Alternatives II, III, IV, and V could cause average benzene derivative prices to rise .04, .13, .37, and 4.12 percent, respectively. Concerning the burden imposed by the capital control costs, the average percentage increases in capital investment required of new units are .07, .20, .59, and 4.47 for Regulatory Alternative II through V.

The conclusions noted above are based upon observations regarding the market structure and competitive nature of the industry, as well as the demand and supply outlook for benzene and its derivatives. Specific conclusions concerning potential price and investment impacts, resulted from assessing the responses of individual model units to the capital control and annualized costs presented in Chapter 8.

In the sections which follow, the industry structure (Section 9.2.2), demand characteristics (Section 9.2.3), and supply characteristics (Section 9.2.4) are examined so that industry responses to control costs may be assessed. Section 9.2.5 details the methodology employed in deriving the conclusions noted in Section 9.2.6, while Section 9.3 addresses potential macroeconomic impacts.

9.2.2 Industry Structure

As noted in Section 9.1.1, there are currently 74 domestic producers of benzene and the eleven derivatives of benzene dealt with in this analysis. Benzene in its pure form is produced by 32 companies, and benzene, obtained as a by-product in the manufacture of ethylene, is produced by 28 companies. The eleven derivatives of benzene are produced by 50 companies. Production capacity for benzene, ethylene, and the benzene derivatives is concentrated in Texas and Louisiana.

Many of the firms that produce benzene and benzene derivatives are diversified, and involved in industrial sectors other than organic chemicals. Some of the firms rank among the largest in the world. Oil companies play a particularly important role in the production of benzene and some of its derivatives. One industry source estimates that oil companies presently account for about 85 percent of domestic production capacity for benzene.[34]

As is the case with most chemicals, the production of benzene and its derivatives tends to be dominated by a relatively small number of firms. The degree of dominance in the various product areas is illustrated by the concentration ratios presented in Table 9-21. For each chemical, the table shows the precentages of production capacity accounted for by the top two and top four companies (for benzene and ethylene, percentages for the top eight are also given, because of the greater number of firms involved). In the case of benzene, the top two companies account for 18 percent of production capacity, while the top four companies account for 34 percent. The eight-firm ratio is 58 percent. For ethylene, which has a total of 28 producers, the two- and four-firm ratios are 23 and 43 percent, respectively. The ratio at the eight-firm level is 68 percent. With respect to the eleven benzene derivatives, the numbers of producers range from one to fifteen. In the cases of hydroquinone and resorcinol, there is only one producer involved in each, and the concentration ratios are therefore 100 percent. For the other derivatives, the two-firm ratios range from 34 percent for cumene (12 firms) to 73 percent for linear alkylbenzene (4 firms). The four-firm ratios range from 59 percent for ethylbenzene (15 firms) to 100 percent for linear alkylbenzene.

Many of the firms that produce benzene and benzene derivatives are vertically integrated organizations which capitvely consume much or even all of their output in the manufacture of other products. For example, it is estimated that approximately 54 percent of the benzene produced domestically in 1977 was consumed captively.[26] In product areas where the degree of captive use is high, the merchant market for the chemical in question tends to be dominated by a small number of high volume sellers.

The existing market structures for benzene, ethylene, and benzene derivatives are reinforced by the existence of significant barriers to entry. Over the years, there has been a trend in the chemical industry towards constructing larger and larger plants in order to take advantage of both new technologies as well as economies of scale. Important economies can be

Table 9-21. CONCENTRATION RATIOS[a] FOR BENZENE, ETHYLENE, AND BENZENE DERIVATIVES

Chemical	# of firms	Concentration ratio (%) 2 firm	Concentration ratio (%) 4 firm
Benzene[b]	32	18	34
Ethylene[c]	28	23	43
Benzenesulfonic Acid	4	d	100
Chlorobenzene	8	56	87
Cumene	12	34	63
Cyclohexane	9	54	72
Ethylbenzene	15	35	59
Hydroquinone	1	100	-
Linear Alkylbenzene	4	73	100
Maleic Anhydride	8	41	67
Nitrobenzene	8	47	82
Resorcinol	1	100	-
Styrene	10	45	74

[a] Ratios calculated from production capacity data presented in Table 9-1. The two (four) firm ratios indicate the percentage of total productive capacity controlled by the two (four) largest producers of each chemical.

[b] Ratio for top 8 firms is 58 percent.

[c] Ratio for top 8 firms is 68 percent.

[d] Productive capacity data not available.

realized in areas such as the purchase of raw materials, spreading overhead, and achieving lower capital requirements per unit of capacity. The effect of these economies is evidenced by the fact that as plant sizes have increased, unit costs have declined. What this situation means to a new firm hoping to enter a merchant market is that in order to compete with the same unit costs, it must be able to achieve the same scale of production, thus requiring the considerable financial resources needed to construct a large facility. Secondly, in order to justify such an investment, the firm must be able to capture a sizeable share of the market. The barriers to entry can be heightened further by the presence of captive consumption, which reduces the potential of the merchant market.

It should be noted that despite the trend toward larger plants, the chemical industry does have a number of smaller plants which operate effectively in their respective product markets. But, in general, these tend to be older plants, which may be fully depreciated. Often, such small plants provide chemicals for captive use. Given the importance of assured supplies of raw materials in the chemical industry, many firms would be reluctant to abandon internal sources of supply to gain favorable, but relatively small decreases in costs.[35]

When new firms do begin production of a chemical, it is frequently for purpose of vertical integration. In these cases, the manufacture of a chemical is initiated in order to supply the firm's internal demand for an intermediate chemical. Another possible avenue for the entry of new firms is through technological change, which may provide an immediate cost advantage. This has not been that important in recent years, however.[35]

The market structures for benzene and benzene derivatives may be characterized as oligopolistic, that is, a small number of participating firms and/or high concentration ratios, with recognition on the part of participating firms that their decisions are interdependent. In general, price changes tend to be initiated by a price leader (or leaders); however, the price increases may be withdrawn if the other participants in the product market do not follow the lead. Prices are usually set as simple percentage markups over costs, or on the basis of target rates of return.[36]

In many industries, price is the most important factor in competition, although in the chemical industry its importance tends to be reduced by three factors: 1) joint product cost accounting; 2) low price elasticity of demand; and 3) the consumer's interest in an uninterrupted supply.[37] In the case of the first factor, the basic point is that it is often difficult for chemical firms to assign costs to any single product because of the complex, interrelated nature of chemical production processes, in which both variable and fixed costs must be apportioned between several different products manufactured at a single plant. Given this type of situation, the price of a particular product can become almost an arbitrary matter as long as the combined prices of the joint products yield the firm's desired return. The second factor, low price elasticity of demand, reduces the importance of price competition since it implies that product demand tends to be insensitive to changes in price. The basic reason for low price elasticity of demand is the absence of substitutes to which customers could switch in the face of price increases. As will be discussed in Section 9.2.3.13, the price elasticity of demand for benzene and benzene derivatives tends to be low. With regard to the third factor, the consumer's interest in an uninterrupted supply, it generally is the case that consumers of chemical products are more sensitive to interruptions in supply than increases in price. This tendency is reflected in the fact that most chemicals are sold under long-term contracts which insure the customer of a secure supply. In periods when there are supply shortages, producers generally grant preferential treatment to their long-term customers. This policy has the effect of discouraging customers from switching suppliers when small differentials in price occur.

9.2.3 Demand Characteristics

9.2.3.1 Benzene. At the present time, the largest uses for benzene are ethylbenzene/styrene (51%), cumene/phenol (17%), cyclohexane (15%), and nitrobenzene/aniline (4%) as noted in Figure 9-1. The major end uses for these benzene derivatives are in packaging, consumer goods, toys, and disposables, which account for about 25 percent of the benzene produced domestically. Other major areas of end use are transportation and household goods, each of which accounts for about 17 percent of benzene consumption.[27] In 1977, about 54 percent of the benzene produced domestically was captively consumed.

Between 1950 and 1974, the consumption of benzene increased cyclically at an average annual rate of about 9 percent. In 1975, consumption plummeted by more than 30 percent, and while 1976 witnessed a substantial recovery, consumption was still below the peak levels attained in 1973 and 1974.[38]

Continued growth in demand is expected, but at a lower rate compared to earlier years. It is estimated that the demand for benzene from all sources (extraction from catalytic reformate, toluene dealkylation, toluene disproportionation, and processing from pyrolysis gas) will grow at a rate of from 5 to 5.5 percent per year between 1977 and 1985.[39] Ethylbenzene/styrene is expected to continue to be the largest use of benzene, followed by cumene/phenol and cyclohexane.

Production capacity is expected to remain adequate through 1982-83; however, benzene may become scarce as the demand for unleaded gasoline increases. As noted in Section 9.1.8.1, the total demand for gasoline is growing slowly or not at all, while the demand for unleaded gasoline is increasing rapidly. With increased production of unleaded gasoline, the amount of aromatics needed by refiners will increase.

9.2.3.2 Benzenesulfonic Acid. Benzenesulfonic acid is primarily used in the production of phenol, with lesser amounts consumed in the manufacture of dyes, or as catalysts. No data on past consumption or future demand are available. According to one source,[38] the product will continue to be used in the commercial production of phenol, however no appreciable increase in consumption for this use is anticipated. Dye and catalyst use are also expected to remain small.

9.2.3.3 Chlorobenzene. The principal chlorobenzene product is monochlorobenzene, with smaller amounts of ortho-and para-dichlorobenzene being co-produced. The consumption of monochlorobenzene declined from a high of 174 Gg in 1960 to an estimated 159-163 Gg in 1976. This drop was due to: 1) the replacement of monochlorobenzene by cumene as an intermediate in the production of phenol, and 2) the decline in the production of the pesticide DDT. The demand for monochlorobenzene is expected to increase, but at an annual rate of no more than two percent through 1981.[4] For chlorobenzenes as a whole, demand is projected to grow at a rate of 1.5 percent per year through 1983 (refer to Section 9.1.8).

9.2.3.4 Cumene. Nearly all of the cumene produced is used in the manufacture of phenol and acetone. Roughly half of domestic production is sold on the merchant market. During the 1960's, the production of cumene increased at a rate of about 25 percent per year as it replaced benzene sulfonation and chlorination as an intermediate step in the production of phenol. Because most of the domestically-produced phenol is currently made from cumene, the production growth rate has slackened somewhat, and it is anticipated that production will tend to approximate the growth trend for phenol.[9] It is anticipated that the demand for cumene will increase at an average annual rate of 7.5 percent through 1983 (refer to Section 9.1.8).

9.2.3.5 Cyclohexane. Most of the cyclohexane consumed in the U.S. is used in the production of nylon fibers and resins (these are the principal end uses for adipic acid, caprolactam, and 1,6-hexamethylenediamine, which are made from cyclohexane). Between 1971 and 1974, total consumption of cyclohexane increased at an average annual rate of 5.9 percent, from 814 Gg to 966 Gg. In 1975, consumption fell by 12.7 percent to 844 Gg. The following year, there was a reversal, with consumption increasing by 13.4 percent to 957 Gg.[2] The demand for this chemical is projected to grow at an average annual rate of 5.0 percent (refer to Section 9.1.8).

9.2.3.6 Ethylbenzene. Virtually all ethylbenzene is consumed captively in the production of styrene. Over the period 1960-1972, consumption of ethylbenzene increased at an average annual rate of 10.8 percent. From 1972 through 1974, domestic consumption remained essentially constant, due to shortages of benzene in 1973 and early 1974, and a decline in the demand for styrene in late 1974. Mirroring the general recession, consumption in 1975 fell by 21.5 percent from the 1974 level. In the following year, there was an increase of 34.9 percent.[10] It is estimated that demand for ethylbenzene will grow at an average annual rate of 6 percent through 1983 (refer to Section 9.1.8).

9.2.3.7 Hydroquinone. Hydroquinone is produced in the U.S. by only one firm, and is used primarily as a rubber antioxidant. It is also used as a photographic developer, dye intermediate, and in other specialty applications which capitalize upon its antioxidant properties. No historical data on demand are available. Projections of future demand are also unavailable. Some sources have indicated that the product has good growth prospects; however, no domestic firms other than Goodyear (the only domestic producer at present) have shown any interest. It is reported that Goodyear plans to increase the output of its plant.[38]

9.2.3.8 Linear Alkylbenzene. The dominant use for linear alkylbenzenes (LAB) is as a raw material in the production of linear alkylbenzene sulfonates (LAS). LAS are currently the principal surfactants for home laundry and dishwashing detergents. In 1977, the domestic consumption of LAB for production of LAS amounted to 216 Gg. This was 6.4 percent more than the 203 Gg consumed in 1975. The future demand for LAB is completely dependent upon the fortunes of LAS.[8] One projection calls for a growth in demand on the order of 2 percent per year through 1983 (refer to Section 9.1.8).

9.2.3.9 Maleic Anhydride. The largest use for maleic anhydride is in the production of unsaturated polyester resins, with secondary uses in the production of fumaric acid and agricultural chemicals. Most of the output of domestic producers is sold on the merchant market. Between 1968 and 1973, U.S. consumption of maleic anhydride increased at an average annual rate of over 9 percent, going from 83 Gg to 128 Gg. Most of this growth was due to increased use for the manufacture of unsaturated polyester resins. In the following year, growth dropped to 7 percent because of feedstock shortages and the onset of a general business recession. In 1975, when the full impact of the recession was felt, consumption declined by 28 percent to a level of 98 Gg.[40] Since that time, consumption has risen, and it is estimated that demand will grow at a rate of 11 percent per year through 1983 (refer to Section 9.1.8). The demand for maleic anhydride will continue to be keyed to its use in the manufacture of unsaturated polyester resins. According to one industry source, major gains from unsaturated polyester fibers may be developing in the auto markets. Depending on their timing and the condition of the economy, auto market gains could give unsaturated polyester resins a major boost in the next several years.[41]

9.2.3.10 Nitrobenzene. Approximately 98 percent of the nitrobenzene consumed in the U.S. is used in the manufacture of aniline. In turn, the major uses of aniline are in the manufacture of p,p'-methylene diphenyldiisocyanate (MDI) (52%) and the manufacture of rubber-processing chemicals (28-29%). Most of the nitrobenzene used for aniline is captively consumed. From 1975 to 1978, the production of nitrobenzene increased at an annual rate of over 5 percent, going from 439 Gg to 510 Gg.[7] It is estimated that demand will increase at an average annual rate of 6 percent through 1983 (refer to Section 9.1.8).

9.2.3.11 Resorcinol. Resorcinol is produced in the U.S. by only one company, and is consumed mainly in the production of resorcinol-formaldehyde resins, which are used as high-performance adhesives in the rubber and wood products industries. From 1964 to 1974, domestic consumption of resorcinol increased from 5 Gg to 11 Gg, yielding an average annual growth of approximately 7 percent. In 1975, the recession brought a sharp drop in consumption which was not overcome until 1977.[6] Future growth in demand will depend greatly upon events in the tire industry, the main consumer of resorcinol. Projections of future demand are not available.

9.2.3.12 Styrene. At the present time, nearly all of the styrene produced in the U.S. is consumed in the manufacture of polymers (polystyrene, 54%; styrene copolymer resins, 17%; sytrene-butadiene elastomers, 9%, unsaturated polyester resins, 6%). Over the years 1960-1972, the consumption of styrene increased at an average annual rate of 10 to 11 percent. In 1973 and 1974, growth rates declined substantially, and in 1975, consumption declined 18 percent from the level of the previous year. The lower growth rates in 1973 and 1974 were a reflection of lower styrene production growth rates brought about by shortages of benzene. The drop in consumption in 1975 was due to the general economic recession. By late 1975, market conditions began to improve, and demand rebounded in 1976 to slightly exceed the levels experienced in 1972-1974. It is anticipated that polystyrene will continue to be the dominant end-use for styrene. Growth in this area, however, can be expected to slacken since many markets for polystyrene are maturing, and the product is facing increasing competition from other materials such as paper and other resins.[1] It is estimated that the demand for styrene will grow at an average annual rate of 6 percent through 1983 (refer to Section 9.1.8).

9.2.3.13 Price Elasticity of Demand for Benzene and Benzene Derivatives. Price elasticities of demand for benzene and the benzene derivatives must be evaluated in order to determine the sensitivities of the markets for these products to price increases which could result from the implementation of the regulatory alternatives outlined in Chapter 6. Data on price elasticity is an important input to the model unit analysis (presented in Section 9.2.6), since it provides a basis for determining the ability of firms to pass the costs of regulation to the consumers of benzene and its derivatives.

The price elasticities of demand for benzene and the benzene derivatives were assessed through the use of a qualitative approach involving the examination of four different screening factors. This methodology is based on one which was originally employed in a study prepared by Energy Resources Co., Inc. for the EPA's Office of Solid Waste.[35] For each of the chemicals, the following were examined:

- Historical and projected growth in demand - High rates of growth, especially during periods of price increases, are indicative of a low price elasticity of demand.
- Level of captive consumption - This is indicative of the degree to which the product is insulated from the competitive pressures of the merchant market. A relatively high level suggests that the chemical is less subject to price considerations.
- Potential for substitution - The availability of direct or indirect substitutes increases the price elasticity of demand.
- Level of foreign competition - A high level of import competition increases the extent to which consumers can switch to foreign supplies when the prices of domestic products increase.

As part of the evaluative procedure, recognition was given to the fact that all of the chemical products considered are used mainly as primary feedstocks or intermediates. Because of heavy investments in existing processes, consumers of primary feedstocks and intermediates have a stake in the continued availability of these inputs. Generally, there is a tendency on the part of such consumers to be more sensitive to supply interruptions than they are to price increases. To the extent that this is the case, the price elasticity of demand will tend to be reduced. The sensitivity of chemical consumers to price increases can also be reduced by non-price factors such as product quality, effectiveness in use, and stability of supply.

The results of the qualitative analysis are presented in Table 9-22. In all cases, the price elasticity of demand is determined to be low.

9.2.4 Supply Characteristics

At present it appears the existing benzene and benzene derivative productive capacity, augmented by projected additions to capacity (Table 7-9)

Table 9-22. QUALITATIVE EVALUATION
OF PRICE ELASTICITY OF DEMAND

Product	Evaluative factors				
	Demand growth[a]	Captive consumption	Potential for substitution	Foreign competition	Price elasticity of demand
Benzene	1950-1974, 9% per year. Decline of more than 30% in 1975. Recovery followed. Projected 5-5.5% per year over period 1977-1985. Continuing upward movement of prices.	Substantial. Estimated to be more than 50% of production.	Main uses are ethylbenzene/styrene, cumene/phenol, & cyclohexane. No good substitutes for benzene as raw material for these. Some indirect substitution possible-e.g. substitution of polyester fibers for nylon fibers.	Imports small.	Low
Benzenesulfonic Acid	No data available on historical or projected demand growth. Small amount of growth anticipated.	No data available, but captive consumption appears to be important.	Main use is an intermediate in production of phenol. Only one domestic producer by this route. Dominant route to phenol is via cumene.	None	Low
Chlorobenzene	Principal chlorobenzene product is monochlorobenzene. From 1960-1976, demand for monochlorobenzene declined from 174 Gg to 159-163 Gg. For chlorobenzenes as whole, growth projected at 1.5% per year over period 1977-1985. Prices have been relatively stable in recent years.	Much of monochlorobenzene production consumed captively. Ortho-& para-dichlorobenzenes mainly sold.	No direct substitutes available in current applications. Some indirect substitution at end-product level may be possible in future.	Imports negligible.	Low

Table 9-22. QUALITATIVE EVALUATION OF PRICE ELASTICITY OF DEMAND (Continued)

Product	Evaluative factors				Price elasticity of demand
	Demand growth[a]	Captive consumption	Potential for substitution	Foreign competition	
Cumene	During 1960's, about 25% per year. With maturation of phenol markets, growth has slowed somewhat. Growth projected at 7.5% per year over period 1977-1983. Upward movement in prices.	About 50% consumed captively.	Other routes to phenol exist, but cumene is preferred.	Substantial amounts of cumene are imported.	Low
Cyclohexane	1971-1974, 5.9% per year. Decline in consumption in 1975, followed by reversal in 1976. Growth projected at 5% per year over period 1977-1983. Prices continuing to move upward.	Mainly sold on merchant market.	Limited substitution possible. Adipic acid can be made from phenol, but this is not an economic substitute. Several other routes are available in production of HMD. Acrylic and polyester fibers can be substituted for nylon.	Imports negligible.	Low
Ethylbenzene	1960-1972, 10.8% per year. Consumption constant from 1972 to 1974. Big drop in 1975, followed by reversal in 1976. Future growth projected at 6% per year through 1983. Price not a factor since most ethylbenzene consumed captively.	Virtually all production captively consumed for styrene.	No substitute for ethylbenzene in production of styrene.	Imports negligible.	Low

Table 9-22. QUALITATIVE EVALUATION
OF PRICE ELASTICITY OF DEMAND
(Continued)

Product	Evaluative factors				Price elasticity of demand
	Demand growth[a]	Captive consumption	Potential for substitution	Foreign competition	
Hydroquinone	No historical data available. Projections also unavailable. May have growth prospects. Only one domestic producer at present.	Both captive use & sale on merchant market. Breakdown unknown.	No substitutes.	Not a factor	Low
Linear Alkylbenzene	1975-1977, slightly more than 3% per year. Estimated growth of 2% per year over period 1977-1983. Price has risen somewhat in recent years.	Both captive use and sale on merchant market. Breakdown unknown.	Main use is in production of linear alkylbenzene sulfonates. No substitution possible in this use.	Imports negligible.	Low
Maleic Anhydride	1968-1973, over 9% per year. In 1974, growth slowed to 7%. In 1975, consumption dropped 28%. Recovery since then. Growth projected at 11% per year over period 1977-1983. Price has increased greatly since 1974, and is continuing upward.	Produced mainly for merchant market.	No direct substitutes in production of unsaturated polyester resins, fumaric acid, and agricultural chemicals.	Imports negligible.	Low

Table 9-22. QUALITATIVE EVALUATION
OF PRICE ELASTICITY OF DEMAND
(Concluded)

Product	Evaluative factors				Price elasticity of demand
	Demand growth[a]	Captive consumption	Potential for substitution	Foreign competition	
Nitrobenzene	1975-1978, 5% per year. Projected growth of 6% per year over period 1977-1983. Price has been gradually increasing.	Most consumed captively in manufacture of aniline.	Aniline can be produced from ammolysis of chlorobenzene, but this source dependent on surplus of chlorine & sales of by-product ammonium chloride.	Imports negligible.	Low
Resorcinol	1964-1974, about 7% per year. In 1975, sharp drop in consumption, which was not overcome until 1977. Projection of future demand not available. Price has been advancing.	Degree of captive use not known. Appears that sale on the merchant market is important.	No substitutes.	Imports negligible.	Low
Styrene	1960-1972, 10-11% per year. Drop in growth rates in 1973 & 1974. In 1975, consumption declined 18% from previous year. Reversal of downward trend in 1976. Growth projected at 6% per year through 1983.	Captive use estimated to be around 60%.	No good substitutes for styrene available at present time.	Imports negligible.	Low

[a] See discussion in Sections 9.2.3.1 to 9.2.3.12 for sources of these data.

will be capable of satisfying the growth in demand as discussed in the previous section. Therefore, while the price of benzene and its derivatives may rise due to increments in crude oil prices, there is no reason to suspect additional price pressure due to supply based market disruptions over the forecast period.

It is, however, important to note two elements which will have a strong influence upon the future proportions of benzene derived from the major petroleum sources. First, the demand for the octane enhancing qualities of petroleum reformate will increase with the rising demand for unleaded gasoline. It has been projected[42] that the unleaded proportion of the total gasoline supply will reach about 75 percent by 1985. Second, the supply of benzene from pyrolysis gasoline (a by-product of ethylene production) will increase as new, larger ethylene plants, using heavier feedstocks, come on-stream.[42] While the former may restrict the availability of petroleum reformate as a benzene feedstock, the latter should increase the benzene producing capabilities of ethylene sources. The combined effect of these market developments will serve to increase that portion of the total supply of benzene attributed to pyrolysis gasoline, while the portion contributed through petroleum reformate will decline.

9.2.5 Economic Impact Methodology

9.2.5.1 Model Units and Economic Impacts. In the following sections the economic implications of applying the regulatory alternatives upon the industry, as represented by the model units defined in Chapter 6, are discussed. Impacts are estimated in terms of the increased capital requirements of, and the potential price increases associated with, each model unit under the various regulatory alternatives.

Concerning capital availability impacts, the extent to which the capital control costs may increase the total investment required for new plants, has been estimated. With regard to prices, separate analyses have been completed for both existing and new plants, thus recognizing the difference in net annualized control costs for both types of plants. While the methodology employed in the determination of economic impacts is detailed below, the results of this analysis are presented in Section 9.2.6.

9.2.5.2 Price Impacts Under Full Cost Pricing. In the estimation of maximum potential product price increases resulting from the alternatives, the full pass through of control costs, to the consumers of benzene and its derivatives, has been assumed for all regulatory alternatives. This full cost pricing assumption is supported by the low price elasticity of demand conclusions detailed in Section 9.2.3.13. The methodology employed in the estimation of price impacts is detailed below while the price impacts themselves are presented in Section 9.2.6.1.

Price increases for each chemical produced at each model unit have been estimated by expressing the net annualized costs of control for each model unit and regulatory alternative (Table 8-11) as a percentage of the annual total revenue of each model unit. These percentages are therefore indicators of the percentage increase in model unit revenues (and thus product prices) required if the net earnings (post control) of each plant are to remain unaffected. While the net annualized cost estimates are presented in Section 8.2.3, the total annual revenues of each model unit have been estimated based on annual output and price estimates as shown in Tables 9-23 through 9-25, and described below.

In the estimation of output, the capacity of each model unit has been taken as the mean capacity of existing plants. The capacities noted in Tables 9-23 through 9-25 are therefore the mean capacities of those plants summarized in Table 9-1. Since Table 9-1 does not distinguish between the three major sources of benzene, the mean benzene capacity of these units has been derived from separate industry surveys.[3,43]

With regard to new vs. existing plant capacities, it has been assumed that the mean capacities of new plants will equal the mean capacities of those plants currently in operation. While economies of scale have in the past and may in the future favor the construction of larger plants, this assumption, in effect, yields conservative estimates of new plant annual revenues.

The annual output of each plant has been estimated based on the assumption that the model units will operate at a rate equivalent to the total capacity utilization rate of all similar plants within the industry. The derivation of capacity utilization rates for each chemical is displayed in Table 9-3 while capacity utilization rates for the individual benzene sources have been derived from industry projections.[27]

Table 9-23. MODEL UNIT ANNUAL REVENUES - MODEL UNIT A (May 1979 Dollars)

Chemical	Capacity (Gg/yr)	Capacity[b] Utilization	Output (Kg/yr)	Price[c] ($/Kg)	Total Revenue
Benzene (toluene dealkylation)	153[a]	.64[e]	97,920,000	.37	$ 36,230,000
Ethylbenzene/Styrene	282[d]	.72	203,000,000	.63	$127,890,000
Cumene	160	.77	123,200,000	.40	$ 49,280,000
Cyclohexane	120	.70	84,000,000	.46	$ 38,640,000
Benzenesulfonic Acid	4	.79	3,160,000	.68	$ 2,149,000
Resorcinol	16	.86	13,760,000	3.09	$ 42,518,000
Maleic Anhydride	23	.56	12,880,000	.88	$ 11,334,000
Ethylene (1 unit)	323	.70	226,100,000	.31	$ 70,091,000

[a] Reference 43, pp. 2-6.

[b] Derived from Table 9-3.

[c] As presented in Table 9-18.

[d] Capacity presented is for styrene.

[e] Reference 27, p. 64.

Table 9-24. MODEL UNIT
ANNUAL REVENUES - MODEL UNIT B
(May 1979 Dollars)

Chemical	Capacity (Gg/yr)	Capacity[b] Utilization	Output (Kg/yr)	Price[c] ($/Kg)	Total Revenue
Benzene (extraction)	80[a]	.83[d]	66,400,000	.37	$ 24,600,000
Chlorobenzene	46	.53	24,400,000	.30	$ 7,300,000
Linear Alkylbenzene	77	.78	60,000,000	.75	$ 45,000,000
Ethylene (2-3 units)	755	.70	528,500,000	.31	$163,800,000

[a] Reference 43, pp. 2-6.

[b] Derived from Table 9-3.

[c] As presented in Table 9-18.

[d] Reference 27, p. 64.

Table 9-25. MODEL UNIT
ANNUAL REVENUES - MODEL UNIT C
(May 1979 Dollars)

Chemical	Capacity (Gg/yr)	Capacity[b] Utilization	Output (Kg/yr)	Price[c] ($/Kg)	Total Revenue
Benzene (pyrolysis gas)	107[a]	.76[e]	81,320,000	.37	$ 30,100,000
Nitrobenzene	63[d]	.61	38,430,000	.79	$ 30,400,000
Hydroquinone	5	.69	3,450,000	3.39	$ 11,700,000
Ethylene (4-5 units)	1136	.70	795,200,000	.31	$246,500,000

[a] Reference 3.

[b] Derived from Table 9-3, except for hydroquinone which is based upon the mean capacity utilization of all plants in Table 9-3.

[c] As presented in Table 9-18.

[d] Capacity presented is for Aniline.

[e] Reference 27, p. 64.

The total annual revenue of each model unit has been estimated according to the output of each plant (in kilograms) and the price per kilogram of each chemical, as noted in Table 9-18. The total revenues calculated in Tables 9-23 through 9-25 are those used as the base for the estimation of maximum product price increases.

9.2.5.3 Capital Availability and Model Unit Investment. All of the previously discussed regulatory alternatives require capital expenditures for both monitoring instruments and control equipment. To allow the assessment of the burden of these additional capital expenditures, upon those firms considering investment in new plants, the capital control cost estimates for each model unit have been compared to the total investment represented by each model unit.

Estimates of total plant investments (including process units, construction and start-up costs, and working capital) were obtained through several sources including: trade journal summaries of construction activity; industry representatives; and vendor/licensor descriptions of process and budgetary economics.

In all cases the investment estimates obtained from the above noted sources were for plant capacities other than the mean model unit capacities noted in 9-23 through 9-25. For this reason, observed investments were adjusted according to the power capacity rule:[44]

$$\frac{\text{Cost of A}}{\text{Cost of B}} = \left[\frac{\text{Capacity A}}{\text{Capacity B}}\right]^{.7}$$

In addition, all investment totals have been expressed in May 1979 dollars, through adjustment according to the Chemical Engineering "Plant Cost Index".[45]

Table 9-26 presents a summary of the investment totals used in the estimation of capital availability impacts. For each plant the total capital investment represents the required investment in both plant and working capital, where working capital requirements are estimated as 15 percent of the investment in plant.[44]

9.2.6 Model Unit Impact Analysis

9.2.6.1 Price Impacts. With the exception of Regulatory Alternative V (i.e., leakless emission control equipment) the full cost pricing policies

Table 9-26. TOTAL CAPITAL INVESTMENT REQUIRED - NEW MODEL UNITS
(Millions of May 1979 Dollars)
(Continued)

Chemical	Capacity (Gg/yr)	Investment In Plant[c]	Investment In Working Capital	Total Capital Investment
Model Unit A				
Benzene (toluene dealkylation)	153	$ 14.6	$ 2.2	$ 16.8
Ethylbenzene/Styrene[a]	282	56.7	8.5	65.2
Cumene	160	21.2	3.2	24.4
Cyclohexane	120	9.9	1.5	11.4
Benzenesulfonic Acid	4	3.8	.6	4.4
Resorcinol	16	9.7	1.5	11.2
Maleic Anhydride	23	20.8	3.1	23.9
Ethylene (1 unit)	323	384.5	57.7	442.2
Model Unit B				
Benzene (extraction)	80	31.4	4.7	36.1
Chlorobenzene	46	11.7	1.8	13.5
Linear Alkylbenzene	77	13.8	2.0	15.8
Ethylene (2-3 units)	775	709.6	106.4	816.0

Table 9-26. TOTAL CAPITAL INVESTMENT REQUIRED - NEW MODEL UNITS (Millions of May 1979 Dollars) (Concluded)

Chemical	Capacity (Gg/yr)	Investment In Plant[c]	Investment In Working Capital	Total Capital Investment
Model Unit C				
Benzene (pyrolysis gasoline)	107	$ 6.8	$ 1.0	$ 7.8
Nitrobenzene/Aniline	63	32.5	4.9	37.4
Hydroquinone	5	22.0	3.3	25.3
Ethylene (4-5 units)	1136	946.8	142.0	1,088.8

[a] Capacity in items of styrene, investment totals are for an integrated ethylbenzene/styrene facility in which all ethylbenzene is consumed in the manufacture of styrene.

[b] Capacity in terms of aniline, investment totals are for an integrated nitrobenzene/aniline facility in which all nitrobenzene is consumed in the manufacture of aniline.

[c] Original plant investment observations were obtained from the following sources:

Benzene (toluene dealkylation) - Ref. 46
Benzene (extraction) - Ref. 52
Benzene (pyrolysis gasoline) - Ref. 55
Benzenesulfonic Acid - Ref. 49
Chlorobenzene - Ref. 53
Cumene - Ref. 47
Cyclohexane - Ref. 48
Ethylbenzene/Styrene - Ref. 56
Ethylene - Ref. 51
Hydroquinone - Ref. 57
Linear Alkylbenzene - Ref. 54
Maleic Anhydride - Ref. 50
Nitrobenzene/Aniline - Ref. 52
Resorcinol - Ref.49

pursued by manufacturers of benzene and its derivatives will have minimal impacts upon the prices of those chemicals. In the tables which follow, the maximum price changes resulting from the alternatives are summarized. Since the alternatives impact derivative chemicals (e.g., styrene, cumene) as well as chemicals used as inputs in the manufacture of derivatives (e.g., benzene, ethylene) the full cost pricing assumption requires that two forms of price impacts be distinguished, that is,

- Price increases attributable to the impacts of the alternatives upon individual chemicals and;
- Price increases attributable to both the impacts of the alternatives upon individual chemicals as well as those resulting from the pass-through of benzene and ethylene price increases to derivatives.

Maximum price increases which can be attributed to the pass-through of control costs to individual chemicals are summarized in Table 9-27. As noted in Section 9.2.5.2, the percentage price increase (based upon May, 1979 prices) for each chemical under each regulatory alternative has been estimated through the expression of net annualized costs (Table 8-11) as a percentage of the appropriate model unit revenue as determined in Tables 9-23 through 9-25.

The relatively low price increases noted in Table 9-27 can be attributed to both low annual control costs in conjunction with relatively high product recovery credits. However, under Regulatory Alternative V, control costs seriously outweigh the value of recovered product to the extent that imposition of this alternative could, under full cost pricing, increase the price of several chemicals by more than 5 percent. For all chemicals included, the potential price increases for the products of new plants are slightly lower than those for existing plants. This is so, since the net annualized control costs for new plants are lower.

Price increases attributable to both impacts upon individual chemicals, as well as the pass through of benzene and ethylene price increases to the manufacturers of derivatives, are referred to as "cumulative price increases." The cumulative price increases are perhaps of greatest concern since they

Table 9-27. PERCENTAGE PRICE INCREASES
(May 1979 Prices)

Chemical	Existing Plants Regulatory Alternative II	 III	 IV	 V	New Plants Regulatory Alternative II	 III	 IV	 V
Model Unit A								
Benzene (toluene dealkylation)	.01	.02	.04	.34	.01	.02	.03	.23
Ethylbenzene/Styrene[a]	<.01	.01	.01	.10	<.01	<.01	.01	.06
Cumene	.01	.02	.03	.25	.01	.01	.02	.17
Cyclohexane	.01	.02	.04	.32	.01	.02	.03	.21
Benzenesulfonic Acid/Phenol[b]	.16	.34	.65	5.67	.14	.27	.56	3.84
Resorcinol	.01	.02	.03	.29	.01	.01	.03	.19
Maleic Anhydride	.03	.07	.12	1.08	.03	.05	.11	.73
Ethylene (1 unit)	<.01	.01	.02	.17	<.01	.01	.02	.12
Model Unit B								
Benzene (extraction)	(.02)	.04	.13	1.48	(.02)	.02	.10	1.01
Chlorobenzene	(.05)	.13	.43	5.00	(.07)	.08	.35	3.39
Linear Alkylbenzene	(.01)	.02	.07	.81	(.01)	.01	.06	.55
Ethylene (2-3 units)	(<.01)	.01	.02	.22	(<.01)	<.01	.02	.15
Model Unit C								
Benzene (pyrolysis gasoline)	(.03)	.05	.17	2.02	(.04)	.02	.13	1.37
Nitrobenzene/Aniline[c]	(.03)	.05	.16	2.00	(.04)	.02	.13	1.36
Hydroquinone	(.09)	.13	.43	5.21	(.11)	.06	.34	3.53
Ethylene (4-5 units)	(<.01)	.01	.02	.25	(.01)	<.01	.02	.17

[a] Price increase for Styrene

[b] Price increase for Phenol

[c] Price increase for Aniline

represent the maximum price increases of benzene derivatives which may result from the full cost pricing policies of manufacturers. Accordingly, cumulative price increases of any benzene derivative can be traced to the costs to control fugitive benzene emissions during the manufacture of both benzene as well as the benzene derivative.

Cumulative price increases have been summarized in Table 9-28. They have been determined through the addition of the appropriate percentage price increases noted in Table 9-27. For example the projected increase in cumene prices under Regulatory Alternative III (.07%) was calculated through the addition of the increase in benzene price from Model Unit C, Alternative III (.05%) and the increase in cumene price from Model Unit A, Alternative III (.02%).

The percentage increases noted in Table 9-28 are conservative for three major reasons. Primarily, the addition of percentage increases implies that benzene is the single input in the manufacture of benzene derivatives. In reality, the contribution of inputs that will be unaffected by the alternatives will minimize the effect of benzene price increases upon the final prices of benzene derivatives. Second, the highest increases in benzene prices (generally that from Pyrolysis Gasoline - Model Unit C) were used in the calculation of cumulative price increases. In reality, the manufacture of derivatives through the use of benzene from Model Units A and B (i.e., Toluene Dealkylation and Solvent Extraction) will entail the pass through of lower price increases. This is especially true for Regulatory Alternatives IV and V. Finally, the recovered product credits used in the determination of net annualized costs are based upon current market prices. Recognizing the past and projected future trends in petroleum and petroleum based product prices, it is quite possible that the value of product recovered under each regulatory alternative will, over the forecast period, increase at a rate higher than the rate of increase in annualized control costs, thus essentially reducing the net annualized cost of each alternative.

9.2.6.2 Capital Availability Impacts. Each of the previously discussed regulatory alternatives requires capital expenditures for monitoring instruments and other control equipment. The need for such equipment requires that potential investors in new plants must obtain additional capital financing above that which would be required in the absence of regulation. In those cases where

Table 9-28. CUMULATIVE PERCENTAGE PRICE INCREASES
(May 1979 Prices)

Chemical	Regulatory Alternative			
	II	III	IV	V
Ethylbenzene/Styrene[a]	.03	.07	.20	2.37
Cumene	.02	.07	.20	2.27
Cyclohexane	.02	.07	.21	2.34
Benzenesulfonic Acid/Phenol[b]	.17	.39	.82	7.69
Resorcinol	.02	.07	.20	2.31
Maleic Anhydride	.04	.12	.29	3.10
Chlorobenzene	(.04)	.18	.60	7.02
Linear Alkylbenzene	.00	.07	.24	2.83
Nitrobenzene/Aniline[c]	(.02)	.10	.33	4.02
Hydroquinone	(.08)	.18	.60	7.23

[a] Price increase for Styrene

[b] Price increase for Phenol

[c] Price increase for Aniline

the additional capital control costs represent a significant increase in total capital requirements, potential investors could, as a result of difficulties in obtaining additional financing, abandon plans for new plant construction.

In order to estimate the extent to which the imposition of the regulatory alternatives could cause significant increases in the capital requirements of new plants, the capital control costs of each regulatory alternative have been expressed as a percentage of the total investment required of each model unit. Estimates of model unit investment requirements have been made through the sources and methodology described in Section 9.2.5.3, while the capital control costs associated with each model unit and regulatory alternative are presented in Table 8-4.

Table 9-29 summarizes the additional percentages of invested capital required of new model units. With regard to the increased capital requirements of Regulatory Alternative II, III and IV, these increases are generally low and cannot be considered potential obstructions to new plant construction. Regulatory Alternative V (i.e., leakless emission control equipment), however, entails much larger increases in required investments, and its imposition could preclude future plant construction. This is especially true in the case of benzene production by way of pyrolysis gasoline. In this case the capital control costs under Regulatory Alternative V, could increase the total capital requirements for such units by 22.49 percent.

9.3 MACROECONOMIC IMPACT

9.3.1 Summary

From the analysis detailed in Section 9.2, it can be concluded that Regulatory Alternatives II, III and IV, will have very little effect either on product prices or the capital investment requirements of related plants. In addition, since market conditions, price inelastic demand, and low maximum potential price increases will allow the full pass through of control costs, it can be conluded that the profitability or market positions of individual manufacturers will not be altered. Regulatory Alternative V, however, holds the possibility of significantly increased prices (for the products of existing and new plants) and increased capital investment requirements for new plants.

9.3.2 Inflationary Impacts

Since the maximum potential price increases (Regulatory Alternatives II, III, and IV) for benzene and its derivatives are low (Table 9-28), price

Table 9-29. PERCENTAGE INCREASE IN NEW PLANT CAPITAL INVESTMENT REQUIRED

Chemical	Regulatory Alternative			
	II	III	IV	V
Model Unit A				
Benzene (toluene dealkylation)	.06	.12	.30	2.08
Ethylbenzene/Styrene	.02	.04	.09	.54
Cumene	.04	.08	.21	1.44
Cyclohexane	.09	.18	.45	3.07
Benzenesulfonic Acid	.23	.45	1.16	7.96
Resorcinol	.09	.18	.46	3.13
Maleic Anhydride	.04	.08	.21	1.47
Ethylene (1 unit)	<.01	<.01	.01	.08
Model Unit B				
Benzene (extraction)	.04	.12	.38	2.91
Chlorobenzene	.10	.31	1.01	7.79
Linear Alkylbenzene	.09	.27	.86	6.66
Ethylene (2-3 units)	<.01	.01	.02	.13
Model Unit C				
Benzene (pyrolysis gasoline)	.22	.86	2.85	22.49
Nitrobenzene/Aniline	.05	.18	.60	4.69
Hydroquinone	.07	.27	.88	6.93
Ethylene (4-5 units)	<.01	.01	.02	.16

increases at the level of consumer products will be imperceptible. Therefore, the application of these regulatory alternatives will not contribute to inflation as measured by the Consumer Price Index.

9.3.3 Energy Impacts

As noted in Section 7.5, each regulatory alternative requires passive controls on equipment handling benzene streams. Under these conditions, no increase in energy consumption is expected.

9.3.4 Employment Impacts

Full cost pricing, on the part of individual manufacturers, will insure that the profitability of existing plants will not be affected by the standard. In addition, the very low increases in capital investment requirements for new plants (Regulatory Alternatives II, III and IV) will not inhibit the construction of new facilities. Under these conditions, the alternatives will not result in either plant closures or reductions in output, and thus the level of employment in the industry will be unaffected.

9.3.5 Fifth Year Annualized Costs

Annualized costs in the fifth year following promulgation (1985), have been estimated for each regulatory alternative, and under no alternative do such costs exceed the $100 million criterion specified in E.O. 12044. Fifth year annualized cost totals have been estimated by summing the annualized costs (Table 8-11) applicable to existing, new, and replacement plants presented in Table 7-9. Fifth year annualized cost totals for Regulatory Alternatives III, IV and V are $2.7, $7.3, and $74.1 million dollars, while Regulatory Alternative II would, if implemented, result in annualized cost reductions due to relatively high product recovery.

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APPENDIX A

EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

APPENDIX A - EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

Date	Nature of Action
August 9-12, 1976	Plant visit to Los Angeles Air Pollution Control District and four Los Angeles area petroleum refineries (Fletcher Oil and Refining Company, Atlantic Richfield Watson Petroleum Refinery, Shell Oil Company Wilmington, Champlin Wilmington Refinery) to obtain background information on miscellaneous sources of hydrocarbon emissions from petroleum refineries.
November 3-4, 1976	Meetings with Exxon Company, USA and Shell Oil Company to discuss EPA request for information on hydrocarbon emission sources and controls.
November 8-10, 1976	Plant visits to four New Orleans, Louisiana, petroleum refineries (Murphy, Gulf, Tenneco, and Shell) to obtain background information on miscellaneous sources of hydrocarbon emissions in petroleum refineries.
November 16-17, 1976	Meetings with Standard Oil of California and Union Oil of California to discuss EPA requests for information on hydrocarbon emission sources and controls.
February 8-14, 1977	Emission source testing at Atlantic Richfield Watson Petroleum Refinery, Carson, California, and Newhall Refining Company, Newhall, California.
April 19-20, 1977	Plant vist to "Refinery A," Corpus Christi, Texas, to gather information for Control Techniques Guideline (CTG) documents.
May 1977	First draft CTG, "Control of Hydrocarbons from Miscellaneous Refinery Sources."
June 8, 1977	Benzene listed as hazardous air pollutant in Federal Register (42 FR 29332).
April 1978	Second draft CTG, "Control of VOC leaks from Petroleum Refining Equipment."
April 26-28, 1978	Radian/IERL Symposium on refinery emissions, Jekyll Island, Georgia.
June 1978	Publication of final CTG, "Control of Volatile Organic Compound Leaks from Petroleum Refinery Equipment."

June 29, 1978	Plant visit to Phillips Petroleum Company, Sweeny, Texas, to collect information on emissions from benzene-related petroleum refinery operations.
June 30, 1978	Plant visit to Exxon Chemical Company, Baytown, Texas, to collect information on emissions from benzene-related petroleum refinery operations.
July 6, 1978	Plant visit to Sun Petroleum Products Company, Toledo, Ohio, to observe and discuss BTX and THD units.
July 13, 1978	Plant visit to Gulf Oil Refinery, Philadelphia, Pennsylvania, to collect information on emissions from benzene-related petroleum refinery operations (UDEX and toluene dealkylation unit).
July 14, 1978	Plant visit to Sun Petroleum Products Company, Marcus Hook, Pennsylvania, to collect information on emissions from benzene-related petroleum refinery operations.
November 13-17, 1978	Plant visit and emission source testing at Sun Petroleum Products Company, Toledo, Ohio, of BTX and HDA units.
December 1978 - January 1979	Telephone survey of refineries to obtain information on accumulator vessel vent emissions.
March 5-8, 1979	Plant visit and emission source testing at Phillips Petroleum Company, Sweeny, Texas, refinery.
March 7, 1979	Plant visit to Phillips Petroleum Company, Sweeny, Texas, refinery and NGL Processing Center.
May 31, 1979	Completion of technical portion of preliminary draft background document and distribution to industry, environmental groups, and other interested persons.
June-July 1979	Public comments on draft background document.
June 20, 1979	Visit to Chevron Company, U.S.A., El Segundo, California, refinery to discuss fugitive VOC emissions.

June 21, 1979	Visit to Atlantic Richfield Company, Carson, California, refinery to discuss fugitive VOC emissions.
July 19, 1979	Chemical Manufacturers Association Fugitive Emission Seminar, Washington, D.C.
October 10, 1979	Carcinogen Policy proposed in Federal Register (44 FR 58642).
March 1980	Completion of Benzene Fugitives preliminary draft background document and distribution to NAPCTAC, industry, environmental groups, and other interested persons.
April 16, 1980	Meeting of the National Air Pollution Control Techniques Advisory Committee to review the Benzene Fugitive Emissions Standard, Raleigh, N.C.
July 14, 1980	Meeting between EPA and the American Petroleum Institute to discuss proposed performance and equipment specifications of Benzene Fugitive Emissions Standard, Durham, N.C.

APPENDIX B

INDEX TO ENVIRONMENTAL CONSIDERATIONS

This appendix consists of a reference system which is cross indexed with the October 21, 1974, Federal Register (39 FR 37419) containing the Agency guidelines for the preparation of Environmental Impact Statements. This index can be used to identify sections of the document which contain data and information germane to any portion of the Federal Register guidelines.

APPENDIX B

INDEX TO ENVIRONMENTAL IMPACT CONSIDERATIONS

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location Within the Background Information Document (BID)
1. Background and Description	
Summary of the Regulatory Alternatives	The regulatory alternatives are summarized in Chapter 1, Section 1.2.
Statutory Authority	Statutory authority is given in Chapter 1, Section 1.1, and Chapter 2.
Industry Affected	A description of the industry to be affected is given in Chapter 9, Section 9.1.
Sources Affected	Descriptions of the various sources to be affected are given in Chapter 3, Section 3.2.
Availability of Control Technology	Information on the availability of control technology is given in Chapter 4.
2. Regulatory Alternatives	
Regulatory Alternative I — No Action (Baseline)	
Environmental Impacts	Environmental effects of Regulatory Alternative I are considered in Chapter 7.
Costs	Costs associated with Regulatory Alternative I are considered in Chapter 8.

(Continued)

INDEX TO ENVIRONMENTAL IMPACT CONSIDERATIONS (Continued)

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location Within the Background Information Document (BID)
Regulatory Alternative II	
Environmental Impacts	Environmental effects associated with Regulatory Alternative II emission control systems are considered in Chapter 7.
Costs	The cost impact of Regulatory Alternative II emission control systems is considered in Chapter 8.
Regulatory Alternative III	
Environmental Impacts	The environmental effects associated with Regulatory Alternative III emission control systems are considered in Chapter 7.
Costs	The cost impact of Regulatory Alternative III emission control systems is considered in Chapter 8.
Regulatory Alternative IV	
Environmental Impacts	The environmental effects associated with Regulatory Alternative IV emission control systems are considered in Chapter 7.
Costs	The cost impact of Regulatory Alternative IV emission control systems is considered in Chapter 8.

(Continued)

INDEX TO ENVIRONMENTAL IMPACT CONSIDERATIONS (Concluded)

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location Within the Background Information Document (BID)
Regulatory Alternative V	
Environmental Impacts	The environmental effects associated with Regulatory Alternative V emission control systems are considered in Chapter 7.
Costs	The cost impact of Regulatory Alternative V emission control systems is considered in Chapter 8.
Regulatory Alternative VI	
Environmental Impacts	The implementation of this alternative would require the elimination of benzene use and production. Benzene emissions would be zero.
Costs	This alternative could not be implemented without closing all plants in several industries. This would not be feasible, and hence costs were not evaluated.

APPENDIX C
EMISSION SOURCE TEST DATA

APPENDIX C - EMISSION SOURCE TEST DATA

C.1 INTRODUCTION

A survey was conducted by EPA to collect data from refineries throughout the United States on leak detection and repairs of equipment emitting volatile organic compounds (VOC) in excess of a defined action level. This appendix summarizes the results of data from seven sources: (1) one reference summarizing valve repair data from four U.S. refineries; (2) Phillips Petroleum Company, Sweeny, Texas; (3) Shell Oil Company, Martinez, California; (4) Union Oil Company of California, San Francisco refinery, Rodeo, California; (5) benzene-producing Units E and F from a U.S. petroleum refinery; (6) ethylene and cumene units at organic chemical manufacturing plants; (7) cyclohexane unit at Exxon Chemical Company, Baytown, Texas; (8) benzene-producing unit at refinery "E," Gulf Coast, U.S.; and (9) benzene-producing unit at AMOCO refinery. For most data sources, the number of pieces of equipment checked and the number of equipment having leaks in excess of a defined action level (usually 10,000 ppm) were determined. When available, repair data were collected so that the number of equipment repairs and non-repairs could be summarized.

Data collected by Monsanto Research Corporation (MRC) concerning fugitive emissions from synthetic organic chemical plant monochlorobenzene units are not summarized in this appendix. This data were never published in final form because of the following: (1) the data exhibited very wide confidence intervals; (2) the experimental design, which was developed for testing several units, was not appropriate for application to the one unit tested; (3) the statistical treatment of the data was questionable; and (4) the quality assurance and control procedures were poorly documented.[1]

C.2 DATA SUMMARIES

C.2.1 Refinery Valve Maintenance Data[2]

Table C-1 presents the results of maintenance data for gas service and light liquid valves from four U.S. petroleum refineries. The number

Table C-1. REFINERY VALVE MAINTENANCE DATA

Action Level: ≥10,000 ppm
Distance from Source: 0 cm
Instrument: Bacharach "TLV Sniffer"

I. Hydrocarbon Leaks Greater Than or Equal to 10,000 ppmv

Source Type	Number of Valves for which Maintenance was Attempted	Number of Valves After Maintenance (≤10,000 ppm)	Percent of Emission Reduction (Leak Rate)
Gas Service Valves			
Undirected Maintenance[a]	8	7	53
Directed Maintenance[b]	7	6	92
Light Liquid Valves			
Undirected Maintenance[a]	4	2	79
Directed Maintenance[b]	4	2	92

[a] As a result of undirected maintenance, valves were tightened, but no concentration data were recorded during maintenance.

[b] As a result of directed maintenance, valves were tightened until emissions were below 10,000 ppm.

Table C-1. REFINERY VALVE MAINTENANCE (Concluded)

Action Level: ≥10,000 ppm
Distance from Source: 0 cm
Instrument: Bacharach "TLV Sniffer"

II. Hydrocarbon Leaks Less Than 10,000 ppmv

Source Type	Number of Valves for which Maintenance was Attempted	Number of Valves With Increased Emissions Rate	Percent of Emission Rate Reduction
Gas Service Valves			
Undirected Maintenance[a]	2	1	66
Directed Maintenance[b]	3	0	54
Light Liquid Valves			
Undirected Maintenance[a]	7	1	56
Directed Maintenance[b]	10	2	76

[a] Valves repaired after undirected maintenance were tightened, but no concentration data were recorded during repair.

[b] Valves repaired after directed maintenance were tightened until emissions were below 10,000 ppm.

Source: Reference 2

of valves on which maintenance was attempted and the number of valves for which screening values after maintenance were below 10,000 ppmv are shown as well as the percentage reduction in leak rates (lb/hr). Maintenance data for leaks less than 10,000 ppmv are also given in Table C-1, showing the number of valves on which maintenance was attempted and the number of valves with increased emissions after maintenance.

Maintenance for the valves was classified as directed or undirected. Directed maintenance valves were those that were tightened and screened until no further reduction in hydrocarbon emissions could be detected by the screening instrument. Undirected maintenance valves were tightened, but no concentration data were recorded during valve maintenance.

C.2.2 Phillips Petroleum Company Data[3]

Equipment leak testing was performed at various units in the Phillips Petroleum Company Sweeny Refinery and Petrochemical Complex, Sweeny, Texas, in March, 1979. All tests were conducted using the Century Instrument Company's Organic Vapor Analyzer (Model OVA - 108) with readings being recorded as the maximum concentration at the seal interface. The number of pieces of equipment leaking at or above 10,000 ppm is shown in Table C-2 by equipment type and unit tested. Table C-3 presents block valve repair data from the ethylene unit of Phillips Sweeny Refinery, and Table C-4 summarizes the repair data.

C.2.3 Shell Oil Company Data[4]

Data were obtained from the refinery valve emissions study at Shell Oil Company's Martinez Manufacturing Complex, Martinez, California. Over 9,000 valves were checked for hydrocarbon leaks. An action level of 10,000 ppm or greater was used to define a valve leak. A summary of leaking valves and repair status is presented in Table C-5. No data were available for detection and repair of leaks from other refinery equipment or for testing methods used in the study.

C.2.4 Union Oil Company, San Francisco Refinery Data[5]

Leak detection and repair data are presented in Tables C-6 through C-8 for refinery valves at Union Oil Company's San Francisco facility in Rodeo, California. All emission measurements were taken 1 cm from the valves, using a VOC detector (Model OVA - 108). Valves leaking at or above 3,000 or 10,000 ppm by volume hydrocarbon were identified, and repairs were attempted. Table C-6 summarizes the number of valves

Table C-2. LEAK DATA FOR THE PHILLIPS PETROLEUM COMPANY, SWEENY REFINERY AND NATURAL GAS LIQUIDS PROCESSING COMPLEX, SWEENY, TEXAS

Action Level: ≥10,000 ppm
Instrument: "OVA-108" VOC detector
Distance from Source: Maximum concentration at seal interface

I. Equipment Type	Number of Equipment Checked	Number of Leaking Equipment	Percent of Equipment Type Leaking
Valves	2,564	222	8.7
Pumps	190	41	21.6
Compressor Seals	33	1	3.0
Drains	150	9	6.0
Control Valves	68	13	19.1
Open-Ended Lines	420	39	9.3
TOTALS	3,425	325	

Continued ....

Table C-2. LEAK DATA FOR THE PHILLIPS PETROLEUM COMPANY, SWEENY REFINERY AND NATURAL GAS LIQUIDS PROCESSING COMPLEX, SWEENY, TEXAS (Concluded)

Action Level: ≥10,000 ppm
Instrument: "OVA-108" VOC detector
Distance from Source: Maximum concentration at seal interface

II. Units Tested

Unit Number	Unit Name	Number of Equipment Checked	Number of Leaking Equipment	Percent Leaking of Unit Tested
4	FCCU Gas Concentration	297	18	6.1
9	Crude Distillation	443	8	1.8
10B	NGL Manufacturing	178	13	7.3
11	High End Point Reformer	847	61	7.2
12	Ethylene Manufacturing	1,096	170	15.5
15	Hexane Isomerization	564	55	9.8
	TOTALS	3,425	325	

Source: Reference 3

Table C-3. PHILLIPS SWEENY REFINERY ETHYLENE UNIT BLOCK VALVE REPAIRS

Action Level: ≥10,000 ppm Instrument: "OVA-108" VOC detector
Distance from Source: Maximum concentration at seal interface

Tag Number	Initial Reading[a]	Date Screened	Maintenance Attempted	Undirected Maintenance Reading	Directed Maintenance Readings 1	2	3	Comments
32	≥10,000	03/06/79	No	≥10,000	1,100			Only checked one valve with tag — meter lines
	≥10,000	03/06/79	No	≥10,000	≥10,000	≥10,000		Only checked one valve with tag
	≥10,000	03/06/79	No	>10,000	≥10,000	≥10,000		Only checked one valve with tag
	≥10,000	03/06/79	Yes	2,000	100			
28	≥10,000	03/06/79	Yes	2,000				
16	≥10,000	03/06/79	Yes	≥10,000	≥10,000	≥10,000	700	Repaired when valve was backseated
10	≥10,000	03/06/79	Yes	100				
7	≥10,000	03/06/79	Yes	≥10,000	≥10,000			Bolts all the way down
4	≥10,000	03/06/79	Yes	200				
367	≥10,000	03/05/79	Yes	500				
366	≥10,000	03/05/79	No					Bolts need replacing
364	≥10,000	03/05/79	Yes	NC[b]				
362	≥10,000	03/05/79	Yes	≥10,000	≥10,000			Leak at gland, not stem — corrosion preventing good seating of gland

Table C-3. PHILLIPS SWEENY REFINERY ETHYLENE UNIT BLOCK VALVE REPAIRS (Continued)

Tag Number	Initial Reading[a]	Date Screened	Maintenance Attempted	Undirected Maintenance Reading	Directed Maintenance Readings			Comments
					1	2	3	
360	≥10,000	03/05/79	Yes	2,000				
359	≥10,000	03/05/79	Yes	4,000				
None	≥10,000	03/05/79	No	>>10,000	>>10,000			Mistagged originally so no initial repair attempted — tightened bolts — needs new packing
358	≥10,000	03/05/79	Yes	NC[b]				
361	≥10,000	03/05/79	Yes	≥10,000	≥10,000			Leak reduced but needs new packing
None	≥10,000	03/05/79	No	≥10,000	≥10,000			Near No. 361 — needs new packing
356	≥10,000	03/05/79	Yes	NC[b]				Was not leaking before maintenance (mistagged)
354	≥10,000	03/05/79	Yes	900				
352	≥10,000	03/05/79	Yes	NC[b]				
65	≥10,000	03/06/79	Yes	3,000				
64	≥10,000	03/06/79	Yes	1,000				
(gland)				≥10,000	≥10,000	7,000		Leak detected by soap solution — missed by instrument operator

Table C-3. PHILLIPS SWEENY REFINERY ETHYLENE UNIT BLOCK VALVE REPAIRS (Concluded)

Tag Number	Initial Reading[a]	Date Screened	Maintenance Attempted	Undirected Maintenance Reading	Directed Maintenance Readings			Comments
					1	2	3	
315	≥10,000	03/06/79	Yes	3,000				
311	NC[b]	03/06/79	Yes	NC[b]				Drain still ≥10,000
316	≥10,000	03/06/79	Yes	≥10,000	2,000			
313	≥10,000	03/06/79	Yes	≥10,000	≥10,000			All the way down on packing
312	≥10,000	03/06/79	Yes	≥10,000	≥10,000	5,000		All the way down on packing
314	≥10,000	03/06/79	No	≥10,000				Bad bolts — need replacing

[a] All readings are in parts per million by volume calibrated to hexane using OVA-108 detector.

[b] NC = No change detected in reading above ambient level.

Source: Reference 3

Table C-4. SUMMARY OF PHILLIPS SWEENY BLOCK VALVE LEAK AND REPAIR DATA

Action Level: ≥10,000 ppm
Instrument: "OVA-108" VOC detector
Distance from Source: Maximum concentration at seal interface

1. Total number of valves with VOC ≥10,000 ppm from unit survey	121
2. Total number of valves tested for maintenance effectiveness	46
% Tested	38%
UNDIRECTED MAINTENANCE[a]	
3. Total number subjected to repair attempts	37
4. Successful repairs (VOC <10,000 ppm)	22
% Repaired	59%
Follow-up DIRECTED MAINTENANCE[b]	
5. Number of valves unrepaired by undirected maintenance subjected to directed maintenance[c]	14
6. Number repaired by follow-up directed maintenance	5
% of unsuccessful repaired by directed maintenance	36%
7. Total number repaired based on undirected maintenance subset (3) above	27
% repaired	73%
8. Total number of repairs including leaks not found before initial maintenance	29
Total % repaired	63%
Total % not repaired	37%

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[a] Valves repaired through undirected maintenance were tightened, but no concentration data were recorded during repair.

[b] Valves repaired through directed maintenance were tightened until VOC emissions were below 10,000 ppmv.

[c] Valves not repaired are valve stems found emitting volatile organic compounds (VOC) at or above 10,000 ppmv.

Source: Reference 2

Table C-5. LEAK AND REPAIR DATA FOR REFINERY VALVES FROM THE SHELL OIL COMPANY, MARTINEZ MANUFACTURING COMPLEX, MARTINEZ, CALIFORNIA[a]

Equipment: Valves
Action Level: ≥ 10,000 ppm
Instrument: "OVA-108" VOC detector
Distance from Source: 1 cm

Valves checked	9,277
Valves leaking	293
(Percent of valves checked)	(3%)
In-service valve repairs attempted	230
Successful repairs[b]	199
(Percent of repairs attempted)	(87%)
Unsuccessful repairs[c]	31
(Percent of repairs attempted)	(13%)

[a] Two sets of emission measurements taken before and after repair during March and April 1979.

[b] Successful repairs resulted in valves leaking below 10,000 ppm.

[c] Unsuccessful repairs are valves still leaking at or above 10,000 ppm after repair.

Source: Reference 4

Table C-6. LEAK AND REPAIR DATA FOR REFINERY VALVES FROM THE UNION OIL COMPANY SAN FRANCISCO REFINERY, RODEO, CALIFORNIA

Equipment: Valves
Total Checked: 5,815
Instrument: "OVA-108" VOC detector
Distance from Source: 1 cm

	Action Level (ppm)	
	≥3,000	≥10,000
Leaking valves	300	215
In-service repairs attempted	158	125
Successful repairs*	107	74
(Percent of repairs attempted that were successful)	(68%)	(59%)
Valves with increased emissions after repair	17	7
(Percent of repairs attempted with increased emissions)	(11%)	(6%)

*Successful repairs resulted in valves leaking below 10,000 ppm.

Source: Reference 5

"successfully repaired" that resulted in emissions below each action level and the number of valves with increased emissions after repair. In cases where emissions were reduced, packing adjustments were made on the valves. Table C-7 presents the number of valves before repair at different action levels and the number of valves having increased emissions after repair. The effects on emissions of repairing valves in the 1,000 through 10,000 ppm range are shown in Table C-8. Emissions from refinery valves within 12 different units and lines are represented. Total emissions (lb/hr) from valves after repair increased 5 percent.

C.2.5 Benzene-Producing Units E and F[6]

Units E and F are part of an intermediate size integrated petroleum refinery located in the North Central United States. Testing was conducted during November 1978 as part of an EPA test program to gather data on leaking sources (defined by a VOC concentration at the leak interface of ≥10,000 ppmv).

An attempt was made to screen all potential leak sources (generally excluding flanges) on an individual component basis with a portable organic vapor analyzer. Normally all pumps were examined, and approximately 33 to 85 percent of valves carrying VOC were screened. All tests were performed with a Century Systems Corporation Organic Vapor Analyzer, Model 108, with the probe placed as close to the source as possible.

Unit E is an aromatics extraction unit that produces benzene, toluene, and xylene by extraction from refined petroleum feedstocks. Unit E is a new unit, and special attention was given during the design and start-up to minimize equipment leaks. All valves were repacked before start-up, adding 2 to 3 times the original packing. All pumps in benzene service had double mechanical seals with a barrier fluid.

Unit F produces benzene by hydrodealkylation of toluene. Unit F was originally designed to produce a different chemical, but it was redesigned to produce benzene.

Table C-9 presents the results of the screening study for Units E and F. Equipment tested included valves, open-ended lines, pump seals, and control valves. Unit E had fewer leaks at or above 10,000 ppmv than Unit F.

Table C-7. ATTEMPTED REPAIR DATA FOR VALVES FROM THE UNION-SAN FRANCISCO REFINERY

Instrument: "OVA-108" VOC detector
Distance from Source: 1 cm

Action Level (ppm)	Total Number of Valves Before Repair	Total Number of Valves With Increased Emissions After Repair	Percent of Valves With Increased Emissions
0 - 999	0	0	---
1,000 - 9,999	33	10	30
≥10,000	125	7	6

Source: Reference 5

Table C-8. EFFECTS ON EMISSIONS OF REPAIRING VALVES IN THE 1,000 - 10,000 PPM RANGE

(Union-San Francisco Refinery, 4/10/79 Data)[a]

Instrument: "OVA-108" VOC detector
Distance from Source: 1 cm

BEFORE REPAIR		AFTER REPAIR	
ppmv	lb/hr[b]	ppmv	lb/hr[b]
5,000	0.04	10,000	0.06
3,000	0.03	300	0.01
5,000	0.04	100	c
5,000	0.04	1,000	0.01
4,000	0.03	7,000	0.05
8,000	0.05	1,000	0.01
4,000	0.03	400	0.01
5,000	0.04	100,000	0.30
4,000	0.03	1,500	0.02
1,000	0.01	1,000	0.01
7,000	0.05	4,000	0.03
9,000	0.06	4,500	0.04
5,000	0.04	400	0.01
4,000	0.03	2,000	0.02
3,000	0.03	2,000	0.02
2,000	0.02	400	0.01
5,000	0.04	1,000	0.01
9,000	0.06	700	0.01
8,000	0.05	10,000	0.06
3,000	0.03	30,000	0.13
4,000	0.03	10,000	0.06
5,000	0.04	10,000	0.06

Table C-8. EFFECTS ON EMISSIONS OF REPAIRING VALVES IN THE 1,000 - 10,000 PPM RANGE

(Union-San Francisco Refinery, 4/10/79 Data)[a]

(Concluded)

BEFORE REPAIR		AFTER REPAIR		
ppmv	lb/hr[b]	ppmv	lb/hr[b]	
5,000	0.04	8,000	0.05	
7,000	0.05	1,500	0.02	
8,000	0.05	2,000	0.02	
4,000	0.03	1,500	0.02	
6,000	0.04	10,000	0.06	
4,000	0.03	9,000	0.06	
4,000	0.03	1,500	0.02	
3,000	0.03	100	c	
TOTALS	1.12		1.19	(+5%)

[a] Source: Reference 5

[b] Emission rate calculations are derived from a correlation of ppmv and lb/hr and not from actual emission rate testing.

[c] Rate is less than 0.005 lb/hr.

TABLE C-9. FREQUENCY OF LEAKS FROM FUGITIVE EMISSION SOURCES IN SYNTHETIC ORGANIC CHEMICAL UNITS E AND F

	Unit E[a,b] BTX Recovery		Unit F[a,b] Toluene HDA	
Equipment Type	Number of Sources Tested	% with Screening Values ≥10,000 ppmv	Number of Sources Tested	% with Screening Values ≥10,000 ppmv
Valves	715	1.1	427	7.0
Open-ended lines	33	0.0	28	11.0
Pump Seals	33[c]	3.0	30	10.0
Control Valves	53	4.0	44	11.0

[a] Source: Reference 6

[b] No data were available for compressor seals, safety/relief valves, or flanges.

[c] Pump seals in benzene service have double mechanical seals.

C.2.6 Ethylene and Cumene Units at Organic Chemical Manufacturing Plants[7]

Three ethylene units and two cumene units were screened for fugitive emissions as part of a program to develop data on the frequency of occurrence of fugitive emissions from various sources in the organic chemical manufacturing industry. Each source was screened by measuring the maximum repeatable concentration of total hydrocarbons (expressed in parts per million by volume) detected at the source with a portable hydrocarbon detector (i.e., Century Systems Models OVA-108 or OVA-128). Sources were screened by a two-person team at an average rate of 1.7 minutes per source (including instrument calibration and repair). Tables C-10 and C-11 present the screening data by source for the cumene and ethylene units.

C.2.7 Cyclohexane Unit at Exxon Chemical Company, Baytown, Texas[8]

Data were supplied by Exxon Chemical Company concerning fugitive emissions at its cyclohexane unit. Sources were "bagged" to measure emissions. The clean air apparatus was combined into a single unit to expedite sampling by reducing set-up time. Calibration of the rotameter for measuring gas flow was performed using a positive displacement wet gas meter.

The total number of valves, pumps and compressor seals, and safety/relief valves were sampled. For valves, however, a soap solution was used to determine leaking components.

Calculations were made to translate the flow rate and concentration data into leak rates for each component sampled from each source type. Confidence limits were calculated at 99.8 percent, higher than normal for engineering applications. No action level was specified.

Table C-12 presents numbers of screened sources, percentage of sources leaking, average emission factors, and 99.8 percent confidence intervals.

C.2.8 Benzene-producing Unit at Refinery "E," Gulf Coast, U.S.[9]

Leaks were measured from seals, valves, control valves, and drains of the aromatics extraction (BTX) unit at refinery "E." A portable hydrocarbon analyzer was used to determine the localized VOC concentration near individual sources and the ambient VOC levels in the unit processing areas. Ambient VOC concentrations along the refinery perimeter were

Table C-10. SCREENING DATA FOR CUMENE UNITS

Action Level: ≥10,000 ppmv
Distance from Source: Unspecified
Instrument: OVA-108 or OVA-128

Source	Service[a]	Number of Screened Sources	Number of Sources ≥ 10,000 ppmv	Percentage of Sources Leaking ≥10,000 ppmv[b]	95% Confidence Interval
Flanges	Gas	367	19	5.2	3.2-8.1
	Liquid	568	9	1.6	0.7-3.0
Process Drains	Gas	6	0	0.0	0.0-45.9
	Liquid	31	1	3.2	0.1-16.7
Open-Ended Valves	Gas	6	0	0.0	0.0-45.9
	Liquid	15	2	13.3	1.7-40.5
Safety/Relief Valves	Gas	1	1	100.0	2.5-100
Pipeline Valves	Gas	448	63	14.1	11.1-17.8
	Liquid	799	84	10.5	8.5-12.8
Pumps	Liquid	25	4	16.0	4.5-36.1

[a] Light liquid service only.

[b] Data were collected on two cumene units. The percentage of sources with total hydrocarbon concentrations ≥10,000 ppmv is a weighted average of the two units.

Source: Reference 7

Table C-11. SCREENING DATA FOR ETHYLENE UNITS[a]

Action Level: ≥10,000 ppmv
Distance from Source: Unspecified
Instrument: OVA-108 or OVA-128

Source	Service[b]	Number of Sources Screened	Number of Sources ≥10,000 ppmv	Percentage of Sources Leaking ≥10,000 ppmv	95% Confidence Interval
Flanges	Gas	627	39	6.2	4.5-8.5
	Liquid	407	25	6.1	4.0-8.9
Process Drains	Gas	8	1	12.5	0.3-52.6
	Liquid	407	4	1.0	0.3-2.5
Open-Ended Valves	Gas	305	37	12.1	8.7-16.4
	Liquid	214	41	19.2	11.8-21.1
Safety/Relief Valves	Gas	51	2	3.9	0.5-13.5
	Liquid	11	1	9.1	0.2-41.3
Pipeline Valves	Gas	6294	932	14.8	13.9-15.8
	Liquid	4176	969	23.2	21.8-24.7
Pumps	Liquid	78	20	25.6	16.4-36.8
Compressors	Gas	17	1	5.9	0.2-28.7

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[a] Data were collected on three ethylene units. Percentage of sources with total hydrocarbon concentrations ≥10,000 ppmv is a weighted average of the three units.

[b] Light liquid service only.

Source: Reference 7

Table C-12. SCREENING DATA FOR CYCLOHEXANE UNIT AT EXXON CHEMICAL COMPANY, BAYTOWN, TEXAS

Action Level: Unspecified

Source	Number of Screened Sources	Percentage of Sources Leaking	Emission Factor (kg/hr)	99.8% Confidence Interval (kg/hr)
Valves				
Gas	136	32	0.017	0.008-0.035
Liquid[a]	100	15	0.008[b]	0.003-0.007[b]
Safety/Relief Valves	15	87	0.064	0.013-0.500
Pumps				
Liquid[a]	8	83	0.255	0.082-0.818
Compressors	NA	100	0.264	0.068-1.045

[a] Source handles light liquid only; cyclohexane unit does not handle heavy streams. Total vapor pressure is 3 psia or higher.

[b] Note that the mean emission factor does not fall within the 99.8 percent confidence interval. This discrepancy existed in the Exxon report (reference 8).

Source: Reference 8

also measured and recorded. Walkthrough surveys were conducted, but due to high background readings, the results for the BTX unit could not easily be evaluated. Individual component surveys were conducted at 5 cm from the potential leak source. Previous studies have indicated that a concentration of 1,000 ppmv at 5 cm is approximately equivalent to a concentration of 10,000 ppmv at 0 cm.[10] For the BTX unit, 6 percent of the 122 components surveyed were found leaking at greater than 1,000 ppm VOC emission concentration.

C.2.9 Benzene-producing Unit at the Amoco Texas Refining Company, Texas City, Texas[11]

Leaks were measured form seals, valves, control valves, and drains of the aromatics extraction (BTX) unit at the Amoco Refining Company, Texas City, Texas. A portable hydrocarbon analyzer was used to determine the localized VOC concentration near individual sources and the ambient VOC levels in the unit processing areas. Individual component surveys were conducted at 5 cm from the potential leak source. Previous studies have indicated that a concentration of 1,000 ppm at 5 cm is approximately equivalent to a concentration of 10,000 ppm at 0 cm.[10] Of all the equipment tested in the unit, 4.2 percent of the total valves and 15 percent of the pump seals were found to have concentrations greater than 1,000 ppm at 5 cm.

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3. Equipment Summary from Phillips Petroleum Company, Sweeny, Texas. March 14, 1979.

4. Valve Repair Summary and Memo from R.M. Thompson, Shell Oil Company, Maritnez Manufacturing Complex, Martinez, California, to Milton Feldstein, Bay Area Quality Management District. April 26, 1979.

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APPENDIX D
EMISSION MEASUREMENT AND CONTINUOUS MONITORING

APPENDIX D - EMISSION MEASUREMENT AND CONTINUOUS MONITORING

D.1 EMISSION MEASUREMENT METHODS

To develop data in support of standards for the control of fugitive emissions, EPA conducted leak surveys at six petroleum refineries and three organic chemical manufacturing plants. The resulting leak determination procedures contained in Reference Method 21 were developed during the course of this test program.

Prior to the first test, available methods for measurement of fugitive leaks were reviewed, with emphasis on methods that would provide data on emission rates from each source. To measure emission rates, each individual piece of equipment must be enclosed in a temporary cover for emission containment. After containment, the leak rate can be determined using concentration change and flow measurements. This procedure has been used in several studies,[1,2] and has been demonstrated to be a feasible method for research purposes. It was not selected for this study because direct measurement of emission rates from leaks is a time-consuming and expensive procedure, and is not feasible or practical for routine testing.

Procedures that yield qualitative or semi-quantitative indications of leak rates were then reviewed. There are essentially two alternatives: leak detection by spraying each component leak source with a soap solution and observing whether or not bubbles were formed; and, the use of a portable analyzer to survey for the presence of increased organic compound concentration in the vicinity of a leak source. Visual, audible, or olefactory inspections are too subjective to be used as indicators of leakage in these applications. The use of a portable analyzer was selected as a basis for the method because it would have been difficult to establish a leak definition based on bubble formation rates. Also, the temperature of the component, physical configuration, and relative movement of parts often interfere with bubble formation.

Once the basic detection principle was selected, it was then necessary to define the procedures for use of the portable analyzer. Prior to performance of the first field test, a procedure was reported that conducted surveys at a distance of 5 cm from the components.[3] This information was used to formulate the test plan for initial testing.[4] In addition, measurements were made at distances of 25 cm and 40 cm on three perpendicular lines around individual sources. Of the three distances, the most repeatable indicator of the presence of a leak was a measurement at 5 cm, with a leak definition concentration of 100 or 1000 ppmv. The localized meteorological conditions affected dispersion significantly at greater distances. Also, it was more difficult to define a leak at greater distances because of the small changes from ambient concentrations observed. Surveys were conducted at 5 cm from the source during the next three facility tests.

The procedure was distributed for comment in a draft control techniques guideline document.[5] Many commentors felt that a measurement distance of 5 cm could not be accurately repeated during screening tests. Since the concentration profile is rapidly changing between 0 and about 10 cm from the source, a small variance from 5 cm could significantly affect the concentration measurement. In response to these comments, the procedures were changed so that measurements were made at the surface of the interface, or essentially 0 cm. This change required that the leak definition level be increased. Additional testing at two refineries and three chemical plants was performed by measuring volatile organic concentrations at the interface surface.

A complication that this change introduces is that a small mass emission rate leak ("pin-hole leak") can be totally captured by the instrument and a high concentration result will be obtained. This has occurred occasionally in EPA tests, and a solution to this problem has not been found.

The calibration basis for the analyzer was evaluated. It was recognized that there are a number of potential vapor stream components and compositions that can be expected. Since all analyzer types do not respond equally to different compounds, it was necessary to establish a reference calibration material. Based on the expected compounds and the limited information available on instrument response factors, hexane was chosen as the reference calibration gas for EPA test programs. At the 5 cm measurement distance, calibrations were conducted at approximately 100 or 1000 ppmv levels. After the measurement distance was changed, calibrations at 10,000 ppmv levels were required. Commentors pointed out that hexane standards at this concentration were not readily available commercially. Consequently, modifications were incorporated to allow alternate standard preparation procedures or alternate calibration gases in the test method recommended in the Control Techniques Guideline Document for Petroleum Refinery Fugitive Emissions. Since that time, additional studies have begun to develop response factor data for two instrument types. Based on preliminary results, it appears that methane is a more representative reference calibration material at 10,000 ppmv levels. Based on this conclusion, and the fact that methane standards are readily available at the necessary calibration concentrations, the recommended calibration material for this regulation was changed to methane.

The alternative of specifying a different calibration material for each type stream and normalization factors for each instrument type was not intensively investigated. There are at least four instrument types available that might be used in this procedure, and there are a large number of potential stream compositions possible. The amount of prior knowledge necessary to develop and subsequently use such factors would make the interpretation of results prohibitively complicated. Based on EPA test results, the number of concentration measurements in the range where a variability of two or three would change the decision as to whether or not a leak exists is small in comparison to the total number of potential leak sources.

An alternative approach to leak detection was evaluated by EPA during field testing. The approach used was an area survey, or walkthrough, using a portable analyzer. The unit area was surveyed by walking through the unit positioning the instrument probe within 1 meter of all valves and pumps. The concentration readings were recorded on a portable strip chart recorder. After completion of the walkthrough, the local wind conditions were used with the chart data to locate the approximate source of any increased ambient concentrations. This procedure was found to yield mixed results. In some cases, the majority of leaks located by individual component testing could be located by walkthrough surveys. In other tests, prevailing dispersion conditions and local elevated ambient concentrations complicated or prevented the interpretation of the results. Additionally, it was not possible to develop a general criteria specifying how much of an ambient increase at a distance of 1 meter is indicative of a 10,000 ppm concentration at the leak source. Because of the potential variability in results from site to site, routine walkthrough surveys were not selected as a reference or alternate test procedure.

D.2 CONTINUOUS MONITORING SYSTEMS AND DEVICES

Since the leak determination procedure is not a typical emission measurement technique, there are no continuous monitoring approaches that are directly applicable. Continual surveillance is achieved by repeated monitoring or screening of all affected potential leak sources. A continuous monitoring system or device could serve as an indicator that a leak has developed between inspection intervals. EPA performed a limited evaluation of fixed-point monitoring systems for their effectiveness in leak detection. The systems consisted of both remote sensing devices with a central readout and a central analyzer system (gas chromatograph) with remotely collected samples. The results of these tests indicated that fixed point systems were not capable of sensing all leaks that were found by individual component testing. This is to be expected since these systems are significantly affected by local dispersion conditions and would require either many individual point locations, or very low detection sensitivities in order to achieve similar results to those obtained using an individual component survey.

It is recommended that fixed-point monitoring systems not be required since general specifications cannot be formulated to assure equivalent results, and each installation would have to be evaluated individually.

D.3 PERFORMANCE TEST METHOD

The recommended benzene fugitive emission detection procedure is Reference Method 21. This method incorporates the use of a portable analyzer to detect the presence of volatile organic vapors at the surface of the interface where direct leakage to atmosphere could occur. The approach of this technique assumes that if an organic leak exists, there will be an increased vapor concentration in the vicinity of the leak, and that the measured concentration is generally proportional to the mass emission rate of the organic compound.

An additional procedure provided in Reference Method 21 is for the determination of "no detectable emissions." The portable VOC analyzer is used to determine the local ambient VOC concentration in the vicinity of the source to be evaluated, and then a measurement is made at the surface of the potential leak interface. If a concentration change of less than 2 percent of the leak definition is observed, then a "no detectable emissions" condition exists. The definition of 2 percent of the leak definition was selected based on the readability of a meter scale graduated in 2 percent increments from 0 to 100 percent of scale, and not necessarily on the performance of emission sources. "No detectable emissions" would exist when the observed concentration change between local ambient and leak interface surface measurements is less than 200 ppmv.

The test procedure does not detect benzene specifically; instead, the volatile organic compound concentration is measured. There is commercially available one type of portable analyzer that has the capability of measuring benzene by chromatographic techniques. However, the addition of the requirement that benzene be measured specifically would require more time and more extensive testing support. Measurement of benzene would not yield additional information since the affected facilities are those in which benzene is transported and a measure of organic vapor leakage is indicative of a benzene leak.

Reference Method 21 does not include a specification of the instrument calibration basis or a definition of a leak in terms of concentration. Based on the results of EPA field tests and laboratory studies, methane is recommended as the reference calibration basis for benzene fugitive emission sources in the refining and organic chemical manufacturing industries.

There are at least four types of detection principles currently available in commercial portable instruments. These are flame ionization, catalytic oxidation, infrared absorption (NDIR), and photoionization. Two types (flame ionization and catalytic oxidation) are known to be available in factory mutual certified versions for use in hazardous atmospheres.

The recommended test procedure includes a set of design and operating specifications and evaluation procedures by which an analyzer's performance can be evaluated. These parameters were selected based on the allowable tolerances for data collection, and not on EPA evaluations of the performance of individual instruments. Based on manufacturers' literature specifications and reported test results,[6] commercially available analyzers can meet these requirements.

The estimated purchase cost for an analyzer ranges from about \$1,000 to \$5,000 depending on the type and optional equipment. The cost of an annual monitoring program per unit, including semiannual instrument tests and reporting is estimated to be from \$3,000 to \$4,500. This estimate is based on EPA contractor costs experienced during previous test programs. Performance of monitoring by plant personnel may result in lower costs. The above estimates do not include any costs associated with leak repair after detection.

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APPENDIX E

METHODOLOGY FOR ESTIMATING LEUKEMIA MORTALITY AND MAXIMUM LIFETIME RISK FROM EXPOSURE TO FUGITIVE BENZENE EMISSIONS FROM PETROLEUM REFINERIES AND SYNTHETIC ORGANIC CHEMICAL MANUFACTURING PLANTS

E.1 INTRODUCTION

The purpose of this appendix is to describe the methodology used in estimating leukemia mortality and maximum lifetime risk attributable to population exposure to fugitive benzene emissions from petroleum refineries and synthetic organic chemical manufacturing plants. The appendix is presented in three parts:

- Part E.2, Summary and Overview of Health Effects, summarizes and references reported health effects from benzene exposure. The major reported health effect is leukemia. Mortalities cited in the BID include only the estimated leukemia deaths attributable to exposure to benzene emissions from existing petroleum refineries and synthetic organic chemical plants although other, sometimes fatal, effects are known to result from benzene exposure.
- Part E.3, Population Density Around Petroleum Refineries and Synthetic Organic Chemical Plants, describes the method used to estimate the population at risk; i.e., persons residing within 20 km of existing petroleum refineries and synthetic organic chemical plants.
- Part E.4, Population Exposures, Mortalities, and Risks, describes the methodology for estimating fugitive benzene emissions from model plants, calculating expected population exposures, and estimating number of leukemia deaths and maximum risk of leukemia attributable to fugitive benzene emissions from 133 existing U.S. petroleum refineries and synthetic organic chemical plants.

E.2 SUMMARY AND OVERVIEW OF HEALTH EFFECTS

E.2.1 Health Effects Associated with Benzene Exposure

A large number of occupational studies over the past 50 years have provided evidence of severe health effects in humans from prolonged inhalation exposure to benzene. Some 300 studies[1] of the health effects of benzene have recently been reviewed and analyzed in terms of application to low-level ambient benzene exposures that might occur in a population residing near a source of benzene emissions.

The reviewers concluded that benzene exposure by inhalation is strongly implicated in three pathological conditions that may be of public health concern at environmental exposure levels:

- Leukemia (a cancer of the blood-forming system),
- Cytopenia (decreased levels of one or more of the formed elements in the circulating blood), and
- Chromosomal aberrations.

Leukemia is a neoplastic proliferation and accumulation of white blood cells in blood and bone marrow. The four main types are acute and chronic myelogenous leukemia and acute and chronic lymphocytic leukemia. The causal relationship between benzene exposure and acute myelogenous leukemia and its variants in humans appears established beyond reasonable doubt.[1]

The term "pancytopenia" refers to diminution of all formed elements of the blood and includes the individual cytopenias: anemia, leukopenia, thrombocytopenia, and aplastic anemia. In mild cases, symptoms of pancytopenia are such nonspecific complaints as lassitude, dizziness, malaise, and shortness of breath. In severe cases, hemorrhage may be observed, and death may occasionally occur because of hemorrhage or massive infection. Patients with pancytopenia may subsequently develop fatal, acute leukemia.

Chromosomal aberrations include chromosome breakage and rearrangement and the presence of abnormal cells. These aberrations may continue for long periods in hematopoietic and lymphoid cells. Ample evidence exists that benzene causes chromosomal aberrations in somatic cells of animals and humans exposed to benzene.[2] The health significance of these aberrations is not fully understood. However, aberrant cells have been observed in individuals exposed to benzene who have later developed leukemia. Some types of chromosomal aberrations may be heritable. Quantitative estimates of heritable genetic damage due to benzene cannot be made from data on the frequency of somatic mutations, although this damage may be occurring at concentrations as low as 1 ppm in air.

The review[1] concluded that man may be the only species yet observed to be susceptible to benzene-induced leukemia. Evidence for production of leukemia in animals by benzene injection was considered nonconclusive. Moreover, benzene exposure by oral dosing, skin painting, or inhalation has not been shown to produce leukemia or any other type of neoplastic diseases in test animals, although other effects, including pancytopenia, have been widely observed.

E.2.2 Benzene Exposure Limits

It should be noted that where the health effects described above have been associated with benzene exposure, the exposure has been at occupational levels. That is, the benzene exposure levels associated with the effects have been high (10 ppm up to hundreds of parts per million of benzene, except in a few cases of exposures to 2 to 3 ppm benzene) or they have been unknown.

Benzene exposure was first associated with health effects in occupational settings, so initial attempts to limit benzene exposures were aimed at occupational exposures. With recognition of the toxic effects of benzene and its greatly expanded use after 1920, several occupational exposure limits were established in the United States.[3] These limits, originally in the range of 75 to 100 ppm, were successively lowered as more information on benzene toxicity became known.

For example, the American Conference of Governmental Industrial Hygienists (ACGIH) recommended a benzene threshold limit value of 100 ppm in 1946, 50 ppm in 1947, 35 ppm in 1948, 25 ppm in 1949, and 10 ppm in 1977.[3,4] The National Institute for Occupational Safety and Health (NIOSH) recommended an exposure limit of 10 ppm in 1974 and revised it downward to 1 ppm in 1976.[5] The current Occupational Safety and Health Administration (OSHA) permissible exposure limit is 10 ppm[6] (a lower limit of 1 ppm is currently in litigation*).

Occupational exposure limits were initially established to protect workers from adverse changes in the blood and blood-forming tissues. The most recently recommended or pending limits of 1 ppm and 10 ppm are based on the conclusion that benzene is leukemogenic in man (NIOSH[5] and OSHA[7]) or a suspected carcinogen in man (ACGIH[4]).

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*A benzene standard with a limit of 1 ppm was proposed by OSHA May 27, 1977, (42 FR 27452) and promulgated February 10, 1978 (43 FR 5918). This standard was struck down October 5, 1978, by the U.S. Fifth Circuit Court of Appeals. The U.S. Department of Labor appealed the decision, and the Supreme Court agreed to hear arguments on the case during its fall, 1979, term. No decision has been announced at this writing.

E.2.3 Health Effects at Environmental Exposure Levels

Little information is available on health effects of nonoccupational exposures of the general populace to benzene. Virtually all of the studies cited[1,2] were on the working population (mostly males) exposed to higher than ambient benzene levels on a work cycle. Applying these studies to chronic (24 hours per day) low-level exposure to the general population (including infants, the ill, and the elderly) requires extrapolation.

The recent analysis of benzene health effects[1] concluded that the evidence of increased risk of leukemia in humans on exposure to benzene for various time periods and concentrations was overwhelming but that data were not adequate for deriving a dose-response curve.

However, EPA's Carcinogen Assessment Group (CAG), acknowledging the absence of a clear dose-response relationship, has estimated the risk of leukemia in the general population from low-level benzene exposure.[2] Data from three epidemiological studies of leukemia in workers (mostly adult white males) were used to estimate the risk of developing leukemia. The annual risk factor derived for benzene-induced leukemia was 0.34 deaths per year per 10^6 ppb-person years of exposure.

A no-threshold linear model was used to extrapolate this estimated risk to the low levels (below 5 to 10 ppb) to which some populations may be exposed. For example, if 3 million persons are chronically exposed to 1 ppb benzene, the model predicts there will be 1.02 leukemia deaths (3 × 0.34) per year in that population. Use of a "linear" model means that the model would predict the same number of leukemia deaths among 3 million people exposed to 1 ppb benzene as among 1 million people exposed to 3 ppb.

The risks factor (0.34 deaths per year per 10^6 ppb-person years) was used in estimating the number of leukemia deaths attributable to benzene emissions from petroleum refineries and synthetic organic chemical plants. Other effects of benzene exposure (including deaths from causes other than leukemia) were not included in the estimated number of deaths. The risk factor equated one leukemia case to one death (that is, each case was presumed fatal).

Several sources of uncertainty exist in applying the risk factor. First, the retrospective occupational exposure estimates may be inaccurate. CAG calculated the 95-percent confidence intervals for this risk factor to be 0.17 to 0.66 deaths per 10^6 ppb-person years if exposure estimates in the three studies extrapolated are precisely correct, and 0.13 to 0.90 if exposure estimates are off by a factor of 2. Second, the composition of the exposed populations around petroleum refineries and synthetic organic chemical plants may vary from that of the populations used as a basis for the CAG estimate; the risk factor assumes that the susceptibility to leukemia associated with a cohort of white male workers is the same as that associated with the general population, which includes women, children, the aged, nonwhites, and the ill. Third, the true dose-response relationship for benzene exposure may not be a linear no-threshold relationship at the low concentrations to which the general population may be exposed. Fourth, the risk factor includes only leukemia deaths and not other health risks. No quantitative estimate of the uncertainty in the risk factor due to the latter three factors has been attempted.

E.3 POPULATION DENSITY AROUND PETROLEUM REFINERIES AND SYNTHETIC ORGANIC CHEMICAL PLANTS

The population "at risk" to benzene exposure was considered to be persons residing within 20 km of petroleum refineries and synthetic organic chemical plants. Populations residing within radial distances of 1, 5, 10, and 20 km from each plant were estimated from an existing population file.[8] This file consists of a grid of 1-km^2 cells covering the continental United States, each with an assigned population. The population assigned to each cell was the 1975 estimated population, extrapolated from the 1960 and 1970 populations of the census enumeration district in which each cell occurs, assuming that the population is uniformly distributed within each of the 256,000 census enumeration districts. The population around each plant was determined by summing the populations of all cells occurring in annular areas at radial distances from the plant center of 0.5 to 1 km, 1 to 5 km, 5 to 10 km, and 10 to 20 km. The estimated total populations exposed as a function of distance from the plant site are reported in Reference 8, Table A-5.

There are some uncertainties in the above method. First, the assumption of uniform population distribution, both within enumeration districts and annular areas, may not be precisely correct. For urban areas the assumption is probably reasonably valid, but there is some uncertainty for rural areas 10 to 20 km from the site. Another area of uncertainty is the use of 1960 and 1970 population data. However, these are the latest available in the form required. No attempt was made to quantify the range of variability in the population figures.

E.4 POPULATION EXPOSURES, MORTALITIES, AND RISKS

E.4.1 Summary of Methodology for Calculating Deaths

The locations and descriptions of all 133 known U.S. benzene-using and benzene-producing plants were compiled.[8] From these data, a basic "model" plant was developed. The model plant was assumed to be an intermediate-size processing complex along the Texas-Louisiana Gulf Coast, with 20 benzene-emitting units placed at various plant locations.[10] Fugitive benzene emission rates from equipment leaks at these sources were estimated from data available at the time this analysis was performed.[10]

The omnidirectional and maximum annual average benzene concentrations in ambient air resulting from each benzene-emitting process were determined to a distance of 20 km outside the model plant boundary, according to the Industrial Source Complex (ISC) dispersion model, urban mode 1.[10] Omnidirectional annual average benzene concentrations are averages for all directions from the source. They take into account changes in wind direction throughout the year and so are lower than maximum annual averages, which are the concentrations downwind from the plant in the prevailing wind direction.

Houston meteorological data for the 1973-1975 period were used in the dispersion model. This period was considered representative of poor dispersion conditions in the area, in order to develop a potential worst-case situation.

Ambient air benzene concentrations were estimated originally based on available data for benzene emission rates from petroleum refineries. These concentrations were proportioned with recently developed data on benzene emission rates from refineries and synthetic organic chemical plants.[9]

Several variations of the original model plant were developed on the basis of different combinations of units currently operating in the 133 existing plants. Ambient air benzene concentrations at several distances from each model plant were determined by summing the benzene concentrations (at each distance) contributed by all the processes incorporated into each particular model variation.[8,9] The result was a range of 56 models, each of which closely resembled an existing plant. Each model was then matched with an appropriate plant, on the basis of unit operations.

The population around each actual plant location was then correlated with its modeled benzene concentrations to yield a benzene dose to that population in ppb-person years. The methods for determining populations are described in Part E.3 of this appendix.

From health effects data, the EPA Carcinogen Assessment Group[2] derived a leukemia risk estimate of 0.34 deaths per year per 10^6 ppb-person years from exposure to benzene. The methodology for estimating the leukemia risk factor is described in Part E.2.3 of this appendix.

The leukemia deaths per year attributable to exposure to fugitive benzene emissions from petroleum refineries and synthetic organic chemical manufacturing plants were estimated by multiplying 0.34×10^{-6} deaths per year per ppb-person year exposure times the exposure in "ppb-person years," as described in Part E.4.2. The leukemia deaths so calculated are summarized in Table E-1 for each plant, with a total for all plants of 0.42 deaths per year.

E.4.2 Estimates of Leukemia Deaths

The general equation for estimating the number of leukemia deaths attributable to fugitive benzene emissions from a particular plant (e.g., Plant X) is:[8]

$$\bar{D}_x = \sum_{i = 0.5-1.0}^{10-20} (R)(1/3.2)\ (2)(\Pi)(p_i)(a)(D_{i_2}^{b+2} - D_{i_1}^{b+2})/(b+2)\ , \qquad (1)$$

in which

$\bar{D}_x$ = estimated number of leukemia deaths per year from fugitive benzene emissions from the plant (e.g., Plant X).

R = the risk factor (0.34 deaths per year per 10^6 ppb-person years).[2]

p_i = density of population at risk, in area (i) around Plant X.[8]

D_{i_2} and D_{i_1} = distances from plant to outer edge (D_{i_2}) and inner edge (D_{i_1}) of area i (e.g., for the area 5-10 km from the plant, $D_{i_2} = 10$ km and $D_{i_1} = 5$ km).

(1/3.2) = factor converting μg/m³ to ppb, the units in which R is expressed.

a and b = values describing the dispersion pattern of benzene in air around Plant X, according to the equation $B_i = a\,D_i^b$, in which B_i is the benzene concentration at distance D_i from the plant. Values of a and b are unique to each annular area i around each model plant.

i = the particular area in which p_i occurs (i progresses from the area 0.5 to 1.0 km from the plant to the area 10 to 20 km from the plant).

Σ = summation of deaths per year from all areas (i).

This equation is a mathematically rigorous method for estimating the exposure to the population within any area between D_{i_1} and D_{i_2} km from the plant, taking into account that with constant population density (p_i) more people reside near the outer edge of the area than near the inner edge, and that the benzene concentration (B_i) decreases with distance from the plant. The equation is derived in Reference 8.

Values of a and b were calculated for each annular area for each model plant as follows:

$$b = \frac{\ln(B_{i_2}/B_{i_1})}{\ln(D_{i_2}/D_{i_1})} \quad . \tag{2}$$

$$a = B_{i_2}/(D_{i_2})^b \quad , \tag{3}$$

in which B_{i_1} is the benzene concentration at the inner edge of area i (i.e., at distance D_{i_1}), and B_{i_2} is the benzene concentration at the outer edge of area i (i.e., at distance D_{i_2}). Bi values for each distance (D_i) from each model plant are listed in Reference 8.

Population density (p_i) for a particular annular area around a particular plant is obtained by dividing the total population in that area (P_i) by the area in square kilometers; i.e.:

$$p_i = P_i/[\Pi(D_{i_2}^2 - D_{i_1}^2)] \quad . \tag{4}$$

In summary, P_i values for each plant and annular area are listed in Reference 8. For each annular space around a particular plant, D_{i_2} and D_{i_1} values are taken from Reference 8. B_i values at all distances (D_i) are also taken from Reference 8. Values of b, a, and p_i are calculated from Equations 2, 3, and 4 for each annular area. Then, with Equation 1, exposures in μg/m^3-person years are calculated for each annular area, divided by 3.2 to convert μg/m^3 to ppb, the units in which R is expressed, and multiplied by R to yield the number of deaths in each annular area. These deaths are summed to give $\bar{D}_x$, the annual leukemia deaths attributable to benzene emissions from Plant X.

The total estimated number of leukemia deaths per year attributable to benzene emissions from all plants was determined by the equation:

$$\text{Total estimated number of leukemia deaths/yr } (\bar{D}_t) = \bar{D}_1 + \bar{D}_2 + \ldots + \bar{D}_{133} \quad . \tag{5}$$

The total numbers of estimated leukemia deaths attributable to fugitive benzene emissions from petroleum refineries and synthetic organic chemical manufacturing plants are given in the last column of Table E-1 on a plant-by-plant basis, in deaths per year, assuming current control conditions for benzene emissions. The number of deaths expected under each of the control alternatives can also be derived with the same methodology.

E.4.3 Example of Leukemia Death Calculation

Plant no. 4 was chosen for an example calculation of the number of leukemia deaths attributable to plant fugitive benzene emissions. For a determination of the number of deaths according to Equation 1, numerical values are needed for R, a, p_i, D_{i_2}, D_{i_1}, and b. In turn, for a determination of p_i from Equation 4, the numerical value of P_i must be known for each annular area. For a determination of b and a from Equation 2 and Equation 3, numerical values of ${}^{B}i_{1}$, and ${}^{B}i_{2}$ must be known for each distance.

Calculations are shown in Table E-2. The values in the first three lines of Table E-2 are common to all plants. They show the distances at which concentrations and populations were measured and the risk factor (R). Line 4 shows the population (P_i) in each annular ring, obtained from Table A-5, Reference 8, for Plant 4.

Lines 5 and 6 show the benzene concentrations at various distances from the plant for the applicable model. Table A-1, Reference 8, indicates that Model 2 is used for Plant 4. From Table A-2, Reference 8, the benzene concentrations at each distance are found for Model 2.

Note that concentrations for 1, 5, and 10 km apply to the outer edge (${}^{B}i_{2}$) of one ring and the inner edge (${}^{B}i_{1}$) of the adjacent ring. Note also that the concentrations at 0.1 km are not used in these calculations. The population within 1 km of a plant is assumed to reside in the area 0.5 to 1 km from the plant.

Lines 7 through 11 show the calculations. These are shown below for the outer ring. From Equation 4:

$$p_i = P_i[/\Pi({}^{D}i_2^2 - {}^{D}i_1^2)] = 4,515,175/\Pi(20^2 - 10^2) = 4,791 \ .$$

From Equation 2:

$$b = \ln({}^{B}i_2/{}^{B}i_1)/\ln({}^{D}i_2/{}^{D}i_1) = \ln(0.0251/0.0695)/\ln(20/10) = -1.469 \ .$$

From Equation 3:

$$a = {}^{B}i_2/{}^{D}i_2{}^{b} = 0.0251/(20)^{-1.469} = 2.048 \ .$$

All the values needed for using Equation 1 are now available, so:

Deaths for 10- to 20-km ring only = $(R/3.2)2\Pi p_i a({}^{D}i_2^{b+2} - {}^{D}i_1^{b+2})/(b+2)$,

$\bar{D}_{10-20} = (0.34 \times 10^{-6}/3.2)2\Pi(4,791)(2.048)(20^{0.531} - 10^{0.531})/0.531$, and

$\bar{D}_{10-20}$ = 0.0182 (0.018623 if decimals are retained during calculations) .

The same calculations are made for ranges 0.5 to 1 km, 1 to 5 km, and 5 to 10 km. The total annual leukemia deaths for the plant ($\bar{D}_x$) are the sum of the deaths for each ring; i.e.:

$$\text{Deaths for Plant 4 } (\bar{D}_4) = \Sigma(\bar{D}_{0.5-1} + \bar{D}_{1-5} + \bar{D}_{5-10} + \bar{D}_{10-20}) .$$

$$\bar{D}_4 = 0.001391 + 0.010064 + 0.011609 + 0.018623 .$$

$$\bar{D}_4 = 0.041687 \text{ deaths/yr} .$$

Deaths attributable to fugitive benzene emissions from any of the 133 plants may be calculated in the same manner.

E.4.4 Estimate of Leukemia Risk

The estimated leukemia deaths shown in Table E-1 are based on estimates of mean annual average benzene concentrations around petroleum refineries and synthetic organic chemical manufacturing plants. Because atmospheric dispersion patterns are not uniform, some population groups will receive above-average benzene exposures and will therefore incur a higher risk (or probability) of developing leukemia.

Maximum annual risk is the estimated probability to a person, who is constantly exposed to the highest maximum annual average benzene concentration in the ambient air around a particular source for a year, of developing leukemia because of exposure to benzene emissions from that source. Maximum lifetime risk is estimated by multiplying the maximum annual risk by 70 years.

The maximum lifetime risk of leukemia was calculated for this person, who is assumed to reside at the point of highest maximum annual average benzene concentration outside the model plant with the greatest benzene emissions. This was found to be Model 14 (Table A-2, Reference 8), representing a plant manufacturing nitrobenzene and chlorobenzene. Model 14 was matched to one existing plant--the Monsanto facility at Sauget, Illinois. The maximum risk of leukemia associated with these emissions is calculated as follows.

First, the fugitive benzene emissions from both of these units are determined (Reference 9, Table I-1): 15.79 kg/hr benzene from the nitrobenzene unit and 9.49 kg/hr from the chlorobenzene unit. These units are then assumed to be located in the positions occupied by the highest and second highest benzene-emitting units in the model plant, in order to be consistent with the original model and so ensure a corresponding maximum benzene concentration and location. These are Groups 18-1, 2, and 3, and 17-1, 2, and 3 (Table 1, Reference 10), with 0.124 g/sec total fugitive benzene emissions from Group 18 and 0.0858 g/sec from Group 17.

The maximum annual average benzene concentrations associated with fugitive emissions from Groups 18 and 17 are then taken from Table 3, Reference 10. For both groups, the highest maximum concentrations occur at 0.1 km outside the plant boundary: 8.74×10^{-1} μg/m^3 benzene due to emissions from Group 18, and 9.46×10^{-1} μg/m^3 from Group 17. These emissions, however, are based on the basic model plant emission rates stated in the preceding paragraph (0.124 and 0.0858 g/sec) and must be scaled up proportionately to reflect the benzene emission rates actually estimated for the nitrobenzene and chlorobenzene units (15.79 and 9.49 kg/hr). This process is carried out as follows.

FOR NITROBENZENE

Fugitive benzene emissions estimated from nitrobenzene unit (Reference 9, Table I-1)	= 15.79 kg/hr (4.39 g/sec)
Fugitive benzene emissions from Group 18 (from Table 1, Reference 10)	= 0.124 g/sec
Maximum annual average benzene concentration due to Group 18 (from Table 3, Reference 10)	= 8.74×10^{-1} μg/m^3
Maximum annual average benzene concentration from nitrobenzene unit emissions in Location 18	= $(8.74 \times 10^{-1})(4.39/0.124)$ = 30.94 μg/m^3

FOR CHLOROBENZENE

Fugitive benzene emissions estimated from chlorobenzene unit from (from Table I-1, Reference 9)	= 9.49 kg/hr (2.64 g/sec)

Fugitive benzene emissions from Group 17 (from Table 1, Reference 10) $= 0.0858$ g/sec

Maximum annual average benzene concentration due to Group 17 (from Table 3, Reference 10) $= 9.46 \times 10^{-1}$ μg/m^3

Maximum annual average benzene concentration from chlorobenzene unit emissions in Location 17 $= (9.46 \times 10^{-1})(2.64/0.0858)$

$= 29.11$ μg/m^3

Summing maximum concentrations from both processes gives:

Maximum annual average benzene concentration from Model plant 14 $= 30.94+29.11 = 60.05$ μg/m^3.

This figure is converted from μg/m^3 to ppb by dividing by 3.2, so

Maximum annual average benzene concentration from Model plant 14 $= 60.05/3.2 = 18.7$ ppb.

This figure, 18.7 ppb, indicates that the person most exposed to benzene from any of the 133 plants resides 0.1 km from the boundary of Model plant 14 and receives an exposure of 18.7 ppb continuously, or for 1 person year annually. By applying the risk factor[2] of 0.34×10^{-6} deaths per year per ppb-person year to this exposure, the annual risk can be calculated, viz:

Maximum annual risk of leukemia $= (0.34 \times 10^{-6}$ deaths per year/ppb-person year) × (18.7 ppb-person years), or

Maximum annual risk of leukemia $= 6.36 \times 10^{-6}$.

Because lifetime risk is expressed as a probability to one person of dying of leukemia, the units have been deleted for convenience. Technically, the number represents deaths per year for one person. The lifetime risk of leukemia, assuming a 70-year lifespan, is simply 70 times the annual risk, or:

Maximum lifetime risk of leukemia $= (6.36 \times 10^{-6})(70) = 4.45 \times 10^{-4}$.

The risk associated with emissions from any specific plant or model plant may be calculated in the same manner.

E.4.5 Validity of Estimates

Several uncertainties exist in the estimated number of leukemia deaths and the maximum leukemia risk. Primary sources of uncertainty are in the:

- Risk factor (R),
- Populations at risk,
- Estimated benzene concentrations around plants, and
- Benzene exposure calculations.

Uncertainties in the risk factor (R) are discussed in Part E.2.3, and uncertainties in populations "at risk" (P_i) are discussed in Part E.3. The other factors are discussed below.

E.4.5.1 Estimated Benzene Concentrations. The estimated benzene concentrations are derived from several factors, as follows:

- Configuration of the model plant,
- Emission rates from the model plant, and
- Dispersion patterns of the emissions.

Uncertainties associated with these factors could not be quantified, but their qualitative effects on the estimated number of leukemia deaths are discussed below.

The configuration of the model plant assumes a petroleum refinery of given area (2.5 km^2), with equipment at specific locations and an effective emission height for all fugitive emissions of 2.5 m. Current fugitive emissions from existing plant processes were estimated[9] and uniform emission rates assumed. When the basic model plant was applied to existing plant emissions, it was assumed that benzene concentrations in air varied in direct proportion to plant emissions.

Several sources of uncertainty occur in this model. First, it is unlikely that any plant duplicates the model plant precisely, so variation in locations of units within plant boundaries may be expected. Second, the model used 1973-1975 weather data from Houston (a coastal city) to project dispersion patterns for all existing plants, and did not take into account the effects of terrain. Thus, when applied to hilly, inland areas, the model may introduce inaccuracies. Third, the model assumes there is no loss of benzene from atmospheric reactions or ground level absorption. If such losses occur, the actual concentration of benzene will be less than the estimated values. Fourth, the model was originally developed for refineries and has been applied to synthetic organic chemical manufacturing facilities as well.

A final source of uncertainty is that the model measures benzene dispersion only to 20 km. If the linear risk model[2] is accurate, exposures at distances greater than 20 km, however small, may be important. If such exposures occur, the estimated number of deaths would be higher than estimated here.

It is estimated that benzene concentrations predicted by the dispersion model are accurate to within a factor of 2,[10] barring large inaccuracies in estimated benzene emission rates.

E.4.5.2 Benzene Exposure Calculations. Benzene exposure calculations assume that persons at specific locations are exposed 100 percent of the time to the benzene concentrations estimated to occur at each location. The assumption of continuous exposure to residents introduces some uncertainty, both in estimated number of leukemia deaths and in maximum leukemia risk. No numerical estimates of potential variation are available. Furthermore, the maximum lifetime risk assumes that a particular plant operates at full capacity for 70 years.

There is a discrepancy between the methods used to measure distance from the plant for benzene concentrations and for populations. Benzene concentrations are measured from the plant boundary, and geographic rings of population are measured from the plant center. This discrepancy introduces some imprecision in the "ppb-person years" benzene exposure calculations used to estimate the number of leukemia deaths. The maximum lifetime risk estimate is not affected.

TABLE E-1. ESTIMATED LEUKEMIA DEATHS FROM FUGITIVE BENZENE EMISSIONS FROM PETROLEUM REFINERIES AND SYNTHETIC ORGANIC CHEMICAL MANUFACTURING PLANTS UNDER CURRENT CONTROL CONDITIONS[8]

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
Region II						
1.	American Cyanamid	NJ	Boundbrook	Somerset	10	0.009642
2.	DuPont	NJ	Gibbstown	Glouchester	10	0.018525
3.	Reichhold	NJ	Elizabeth	Union	9	0.004384
4.	Standard Chlorine	NJ	Kearny	Hudson	2	0.041687
5.	Tenneco	NJ	Fords	Middlesex	9	0.001759
6.	Texaco	NJ	Westville	Glouchester	30	0.014268
7.	Allied Chemical[9]	NY	Solvay	Onondaga	2	0.002042
8.	Ashland Oil	NY	North Tonawanda	Niagara	21	0.000130
9.	ICC Industries	NY	Niagara Falls	Niagara	2	0.004375
10.	Commonwealth Oil	PR	Penuelas	---	45	0.004001
11.	Phillips Puerto Rico	PR	Guyama	---	46	0.004001
12.	Puerto Rico Olefins	PR	Penuelas	---	4	0.000575
13.	Union Carbide	PR	Penuelas	---	25	0.004516
14.	Amerada Hess	VI	St. Croix	---	24	0.001568
Region III						
15.	Getty	DE	Delaware City	New Castle	23	0.001063
16.	Standard Chlorine	DE	Delaware City	New Castle	2	0.001999
17.	Sun-Olin	DE	Claymont	New Castle	4	0.001184
18.	Continental Oil	MD	Baltimore	Baltimore	8	0.008464

See footnotes at end of table. (continued)

TABLE E-1 (continued)

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
19.	Atlantic Richfield	PA	Beaver Valley	Beaver	12	0.000258
20.	Gulf Oil	PA	Philadelphia	Philadelphia	52	0.029612
21.	Koppers	PA	Bridgeville	Allegheny	9	0.001924
22.	Koppers	PA	Petrolia	Butler	11	0.000050
23.	Nease Chemical	PA	State College	Centre	1	0.000281
24.	Standard Oil (Ohio)/BP Oil	PA	Marcus Hook	Delaware	48	0.005566
25.	Sun Oil	PA	Marcus Hook	Delaware	56	0.006708
26.	U.S. Steel	PA	Neville Island	Allegheny	9	0.001681
27.	Allied Chemical	WV	Moundsville	Marshall	10	0.002003
28.	American Cyanamid	WV	Willow Island	Pleasants	10	0.000916
29.	Ashland Oil	WV	Neal	Wayne	9	0.000166
30.	Mobay Chemical	WV	New Martinsville	Wetzel	10	0.000671
31.	PPG	WV	Natrium	Marshall	2	0.000153
32.	PPG	WV	New Martinsville	Wetzel	2	0.000375
33.	Union Carbide	WV	Institute	Kanawha	19	0.001677
Region IV						
34.	Jim Walter Resources	AL	Birmingham	Jefferson	1	0.001945
35.	Reichhold Chemicals	AL	Tuscaloosa	Tuscaloosa	1	0.000288
36.	Ashland Oil	KY	Ashland	Boyd	49	0.002214
37.	B. F. Goodrich	KY	Calvert City	Marshall	4	0.000040
38.	Olin Corporation	KY	Brandenburg	Mead	4	0.000049

See footnotes at end of table.

(continued)

TABLE E-1 (continued)

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
39.	Chevron	MS	Pascagoula	Jackson	21	0.000690
40.	First Chemical	MS	Pascagoula	Jackson	10	0.002044
Region V						
41.	Clark Oil	IL	Blue Island	Cook	3	0.001235
42.	Core-Lube	IL	Danville	Vermilion	1	0.000262
43.	Koppers	IL	Cicero	Cook	9	0.007317
44.	Monsanto	IL	Sauget	St. Clair	14	0.037257
45.	National Distiller (U.S.I.)	IL	Tuscola	Douglas	4	0.000033
46.	Northern Petrochemicals	IL	Morris	Grundy	4	0.000081
47.	Reichhold Chemicals	IL	Morris	Grundy	9	0.000076
48.	Shell Oil	IL	Wood River	Madison	21	0.001555
49.	Standard Oil (Indiana)/Amoco[h]	IL	Joliet	Will	9	0.000357
50.	Union Oil (California)	IL	Lemont	Cook	23	0.002669
51.	Dow Chemical	MI	Bay City	Bay	26	0.003289
52.	Dow Chemical	MI	Midland	Midland	13	0.002391
53.	Sun Oil	OH	Toledo	Lucas	56	0.006263
Region VI						
54.	Vertac/Transvaal	AR	Jacksonville	Pulaski	2	0.000045
55.	Allied Chemical	LA	Geismar	Ascension	4	0.000090

See footnotes at end of table.

(continued)

TABLE E-1 (continued)

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
56.	American Hoechst	LA	Baton Rouge	East Baton Rouge	20	0.001632
57.	Cities Service	LA	Lake Charles	Calcasieu	42	0.000784
58.	Continental Oil	LA	Lake Charles	Calcasieu	4	0.000166
59.	Cos-Mar, Inc.	LA	Carrville	Iberville	20	0.000166
60.	Dow Chemical	LA	Plaquemine	Iberville	5	0.000008
61.	Exxon	LA	Baton Rouge	East Baton Rouge	40	0.006369
62.	Gulf Coast Olefins	LA	Taft	St. Charles	4	0.000088
63.	Gulf Oil	LA	Alliance	Plaquemines	48	0.000084
64.	Gulf Oil	LA	Donaldsonville	Ascension	20	0.000179
65.	Pennzoil United (Atlas Processing)	LA	Shreveport	Caddo	23	0.003908
66.	Rubicon	LA	Geismar	Ascension	10	0.000772
67.	Shell Oil	LA	Norco	St. Charles	4	0.000103
68.	Tenneco	LA	Chalmette	St. Bernard	33	0.004497
69.	Union Carbide	LA	Taft	St. Charles	26	0.000538
70.	Sun Oil	OK	Tulsa	Tulsa	54	0.005978
71.	American Hoechst	TX	Bayport	Harris	c	0.000000
72.	American Petrofina of Texas	TX	Port Arthur	Jefferson	22	0.000616
73.	American Petrofina (Cosden Oil)	TX	Big Spring	Howard	53	0.001444

See footnotes at end of table.

(continued)

TABLE E-1 (continued)

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
74.	American Petrofina/ Union Oil of California	TX	Beaumont	Jefferson	39	0.002130
75.	Amoco Chemicals[i]	TX	Chocolate Bayou	Brazoria	4	0.000026
76.	Atlantic Richfield	TX	Channelview	Harris	27	0.003569
77.	Atlantic Richfield (ARCO/Polymers)	TX	Houston	Harris	47	0.011300
78.	Atlantic Richfield (ARCO/Polymers)	TX	Port Arthur	Jefferson	6	0.000359
79.	Charter International	TX	Houston	Harris	43	0.008574
80.	Coastal States Gas	TX	Corpus Christi	Nueces	44	0.000800
81.	Corpus Christi Petrochemicals	TX	Corpus Christi	Nueces	c	0.000000
82.	Cosden Oil	TX	Groves	Jefferson	4	0.000002
83.	Crown Central	TX	Pasadena	Harris	56	0.007757
84.	DENKA (Petrotex)	TX	Houston	Harris	9	0.001650
85.	Dow Chemical	TX	Freeport	Brazoria	29	0.001087
86.	Dow Chemical	TX	Orange	Orange	4	0.000055
87.	DuPont	TX	Beaumont	Jefferson	10	0.002980
88.	DuPont	TX	Orange	Orange	4	0.000148
89.	Eastman Kodak	TX	Longview	Gregg	4	0.000168
90.	El Paso Natural Gas	TX	Odessa	Ector	18	0.001083
91.	El Paso Products/ Rexene Polyolefins	TX	Odessa	Ector	17	0.000587

See footnotes at end of table.

(continued)

TABLE E-1 (continued)

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
92.	Exxon	TX	Baytown	Harris	32	0.002130
93.	Georgia-Pacific Corp.	TX	Houston	Harris	3	0.000419
94.	Goodyear Tire and Rubber	TX	Bayport	Harris	7	0.003867
95.	Gulf Oil Chemicals	TX	Cedar Bayou	Brazoria	5	0.000011
96.	Gulf Oil Chemicals	TX	Port Arthur	Jefferson	36	0.002375
97.	Hercules	TX	McGregor	McLennan	c	0.000000
98.	Howell	TX	San Antonio	Bexar	23	0.004469
99.	Independent Refining Corp.	TX	Winnie	Chambers	23	0.000116
100.	Kerr-McGee Corp. (Southwestern)	TX	Corpus Christi	Nueces	21	0.002053
101.	Marathon Oil	TX	Texas City	Galveston	35	0.002177
102.	Mobil Oil	TX	Beaumont	Jefferson	55	0.003353
103.	Monsanto	TX	Alvin (Chocolate Bayou)	Brazoria	15	0.000192
104.	Monsanto	TX	Texas City	Galveston	28	0.002497
105.	Oxirane	TX	Channelview	Harris	6	0.000926
106.	Phillips Petroleum	TX	Borger	Hutchinson	16	0.000868
107.	Phillips Petroleum	TX	Sweeny	Brazoria	38	0.000241
108.	Quintana-Howell	TX	Corpus Christi	Nueces	48	0.001794
109.	Shell Chemical	TX	Houston	Harris	4	0.000365
110.	Shell Oil	TX	Deer Park	Harris	31	0.004345
111.	Shell Oil	TX	Odessa	Ector	56	0.001633

See footnotes at end of table.

(continued)

TABLE E-1 (continued)

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
112.	Standard Oil (Indiana)[i]	TX	Alvin	Brazoria	5	0.000036
113.	Standard Oil (Indiana)/Amoco	TX	Texas City	Galveston	34	0.003654
114.	Sun Oil	TX	Corpus Christi	Nueces	51	0.002155
115.	Texaco	TX	Port Arthur	Jefferson	37	0.003038
116.	Texaco/Jefferson Chemical	TX	Bellaire	Harris	4	0.000165
117.	Texaco/Jefferson Chemical	TX	Port Neches	Jefferson	4	0.000004
118.	Union Carbide	TX	Seadrift	Calhoun	18	0.000046
119.	Union Carbide	TX	Texas City	Galveston	4	0.000322
120.	Union Pacific/Champlin	TX	Corpus Christi	Nueces	50	0.005486
121.	USS Chemicals	TX	Houston	Harris	4	0.000308
Region VII						
122.	Chemplex	IO	Clinton	Clinton	4	0.000068
123.	Getty Oil	KA	El Dorado	Butler	35	0.000562
124.	Monsanto	MO	St. Louis	St. Louis	9	0.003600
Region IX						
125.	Atlantic Richfield	CA	Wilmington	Los Angeles	41	0.015754
126.	Chevron	CA	Richmond	Contra Costa	23	0.003862
127.	Specialty Organics	CA	Irwindale	Los Angeles	2	0.011570
128.	Standard Oil of California (Chevron Chemical)	CA	El Segundo	Los Angeles	35	0.015163
129.	Union Carbide	CA	Torrance	Los Angeles	4	0.002377

(continued)

See footnotes at end of table.

TABLE E-1 (continued)

Plant code no.	Company (by region)	Location			Model number[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
130.	Witco Chemical	CA	Carson	Los Angeles	8	0.003025
131.	Montrose Chemical	NV	Henderson	Clark	2	0.001527
132.	Stauffer Chemical	NV	Henderson	Clark	1	0.000445
133.	Phillips	TX	Pasadena	Harris	4	0.000070
			Total deaths			0.420656[d,e,f]

[a] Model used to estimate benzene concentrations around plant.

[b] Confidence limits of 95 percent are obtained by multiplying and dividing figures shown by 2.64. This results in a 95-percent confidence interval that assumes the estimated concentrations to which the workers were exposed, as discussed in the CAG report,[2] are within a factor of 2.

[c] Models were not assigned to three plants still under construction.

[d] Total may not be exact past three decimal places due to rounding. Total deaths for some plants differ slightly from those listed in Reference 8, due to correction of a minor mathematical error.

[e] It should be recognized that considerable uncertainty is associated with the cases of leukemia that appear in the table. First, the cases were calculated based on an extrapolation of leukemia risk associated with a healthy white male cohort of workers to the general population, which includes men, women, children, infants, the aged, nonwhites, and the unhealthy. Second, there are uncertainties in estimating the benzene levels to which people in the vicinity of petroleum refineries and synthetic organic chemical manufacturing plants are exposed. Also, the number of cases includes consideration of only one effect of benzene exposure; i.e., leukemia. Benzene exposure has also been indicated to cause aplastic anemia, cytopenias, and the development of chromosomal aberrations. In addition, the benefits to the general population of controlling other hydrocarbon emissions from petroleum refineries and synthetic organic chemical manufacturing plants are not quantified.

TABLE E-1 (concluded)

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[f] This total has been revised since three of the plants in the table should be deleted (see footnotes g-i). This revision represents a decrease of 0.6 percent from the previous total of 0.423091 deaths per year.

[g] Industry sources indicate that Allied Chemical's (Solvay, N.Y.) chlorobenzene unit is no longer in operation. Therefore, the plant should be deleted from the table.

[h] Standard Oil of Indiana's maleic anhydride unit at Joliet, Illinois, should be deleted since it is using butane as a feedstock instead of benzene.

[i] The Amoco Chemical plant at Chocolate Bayou, Texas, and Standard Oil of Indiana at Alvin, Texas (Plant No. 112) are the same plant (2 ethylene units). Therefore, the Chocolate Bayou plant should be deleted from the table.

TABLE E-2. EXAMPLE CALCULATION OF LEUKEMIA DEATHS, PLANT 4

Line no.	Factor	Annular ring around plant (km)				Source of data
		0.5-1	1-5	5-10	10-20	
	GIVEN DATA					
1	Distance to outer ring edge, D_{i_2}(km)	1	5	10	20	Refs. 8, 10
2	Distance to inner ring edge, D_{i_1}(km)	0.5	1	5	10	Refs. 8, 10
3	R, risk factor (deaths/ppb-person yr)	0.34×10^{-6}	0.34×10^{-6}	0.34×10^{-6}	0.34×10^{-6}	Ref. 2
4	Population in annular ring (persons)	7,963	271,100	1,025,093	4,515,175	Ref. 8, Table A-5 for Plant 4
5	Benzene conc. at outer ring edge, B_{i_2}(μg/m^3)	1.24	0.189	0.0695	0.0251	Ref. 8, Table A-2 for Model 2[a]
6	Benzene conc. at inner ring edge, B_{i_1}(μg/m^3)	2.45	1.24	0.189	0.0695	Ref. 8, Table A-2 for Model 2[a]
	CALCULATIONS					
7	Population density, p_i (persons/km^2) $p_i = P_i/[\Pi(D_{i_2}^2 - D_{i_1}^2)]$	3,380	3,596	4,351	4,791	Equation 4
8	b: $b = \ln(B_{i_2}/B_{i_1})/\ln(D_{i_2}/D_{i_1})$	-0.982	-1.169	-1.443	-1.469	Equation 2
9	a: $a = B_{i_2}/(D_{i_2})^b$	1.240	1.240	1.929	2.048	Equation 3
10	Deaths per year in each ring = $(R/3.2)2\Pi p_i a(D_{i_2}^{b+2} - D_{i_1}^{b+2})/(b+2)$	0.001393	0.010064	0.011609	0.018623	Equation 1
11	Total deaths in all rings = $\bar{D}_x$ (deaths/yr)	0.041687[b]				ΣEquation 1

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[a] Model numbers for each plant are shown in Table A-1, Reference 8, and in Table E-1 of this appendix.

[b] This total appears in Table E-1 of this appendix. It also appears in Table A-4, Reference 8, as $41{,}686.54 \times 10^{-6}$.

E.5 REFERENCES

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APPENDIX F

APPENDIX F - ESTIMATES OF BENZENE EMISSIONS AND CONTROL COSTS OF PRODUCT ACCUMULATOR VESSELS

F.1 INTRODUCTION

Product accumulator vessels were discussed in Chapter 3 as a potential source of benzene fugitive emissions. Controlling accumulator vessels by routing the emissions to a closed-vent system was discussed in Chapter 4. No estimates of benzene emissions from or control costs for accumulator vessels have been included in Chapters 7 and 8 because of uncertainties in the number of uncontrolled vents and lack of data on benzene emission rates from uncontrolled vents.

The purposes of this analysis are (1) to estimate the additional benzene emission and control costs of accumulator vessels and (2) to describe the effect of adding these estimates to the ones from all other sources.

F.2 ESTIMATE OF BENZENE EMISSIONS

F.2.1 Uncontrolled Estimates

Benzene emissions from accumulator vessels can be estimated by a method similar to the one described in Chapter 7. The number of accumulator vessels per model unit (containing greater than 10 percent benzene) was estimated by examining flow diagrams and material balances for various benzene processes.

The uncontrolled VOC emission factor estimated for accumulator vessels is multiplied by the number of vessels in each model unit and the weighted factor of percent benzene in each model unit to obtain the uncontrolled benzene emission rate. Table F-1 shows the calculation of the uncontrolled emissions from accumulator vessels by model unit.

F.2.2. Controlled Estimates

Assuming that 95 percent of accumulator vessels are already controlled by a closed-vent system, the controlled emission rates for the baseline alternative (I) are estimated by multiplying the uncontrolled rates by 0.05 (1-0.95). It is not necessary to estimate benzene emissions from accumulator vessels for Regulatory Alternatives III, IV, and V, since 100 percent control efficiencies are already specified for each. The controlled emissions for each model unit under Regulatory

Table F-1. CALCULATION OF UNCONTROLLED BENZENE EMISSIONS FROM ACCUMULATOR VESSELS BY MODEL UNIT

Model Unit	Number of Vessels Per Unit	x	Uncontrolled VOC Emission Factor[a] (Kg VOC/hr)	x	Weighted Percent Benzene[b]	x	Conversion Factor $\left(\frac{Mg/yr}{Kg/hr}\right)$	=	Uncontrolled Benzene Emission Rate (Mg/yr)
A	1		1.23		0.63		8.4		6.5
B	2		1.23		0.55		8.4		11.4
C	2		1.23		0.75		8.4		15.5

[a] Source: Briggs, T. and V.P. Patel. Evaluation of Emissions from Benzene-Related Petroleum Processing Operations. PEDCo Environmental, Inc. Cincinnati, OH. For U.S. Environmental Protection Agency. Research Triangle Park, N.C. Report No. EPA-450/3-79-022. October 1978.

[b] Weighted average benzene concentration for the processes represented by each model unit.

Alternative I are calculated to be 0.33 Mg/yr for Model Unit A, 0.57 Mg/yr for Model Unit B, and 0.78 Mg/yr for Model Unit C.

F.2.3 Nationwide Estimates

Nationwide benzene emissions from accumulator vessels are estimated by multiplying the controlled emissions from each model unit by the number of existing units operating in 1980. The resulting nationwide total under Regulatory Alternative I is presented in Table F-2.

The national accumulator vessel emissions are then added to the national baseline emissions from all other sources as shown in Table 7-9 to yield a combined emission estimate of 8,360 Mg/yr. Adding the accumulator vessel emissions increases the nationwide total by less than 2 percent. Furthermore, the increase in excess incidence of lukemia deaths for the baseline alternative would change only slightly by adding accumulator vessel emissions. The baseline incidence would increase from 0.6300 deaths per year to 0.6384, a change of 1.3 percent per year, as shown in Table F-3.

F.3 CONTROL COST ESTIMATES

Capital and annual costs were calculated for accumulator vent systems for each model unit as presented in Table F-4. Nationwide costs for controlling existing accumulator vessels, as shown in Table F-5, are based on the assumption that 5 percent of existing accumulator vessels are uncontrolled and are tied into existing control devices.

When costs for controlling accumulator vessels are added to the nationwide costs for controlling all other sources (Chapter 8, Table 8-15), the total costs increase only slightly. Table F-6 presents the total capital and (net) annualized costs for Regulatory Alternatives III through V after accumulator vessel costs are added.

Table F-2. NATIONAL BENZENE EMISSIONS FROM ACCUMULATOR VESSELS IN 1980 FOR REGULATORY ALTERNATIVE I

Model Units	Benzene Emissions Per Unit (Mg/yr)	Number of Units Expected in Operation (1980)	Total Benzene Emissions Per Unit (Mg/yr)
A	0.33	145	47.9
B	0.57	72	41.0
C	0.78	24	18.7
		Nationwide Total =	107.6

Table F-3. EFFECT OF ADDING ACCUMULATOR VESSEL EMISSIONS ON BASELINE RISK

	Nationwide Benzene Emission Total (Mg/yr)	Excess Incidence of Leukemia Deaths (deaths/yr)
Other Sources (exluding Accumulator Vessels)	8250	0.6300[a]
Other Sources + Accumulator Vessels	8360	0.6384[b]

[a] Risk for "Other Sources" represents a mid-range of excess incidence of leukemia for the baseline regulatory alternative.

[b] Calculated by multiplying $\frac{8360}{8250}$ by 0.63.

Table F-4. CAPITAL AND ANNUALIZED
COSTS FOR VENT SYSTEMS FOR ACCUMULATOR VESSELS
BY MODEL UNIT

Model Unit[a]	Capital Cost, $[b]	Annualized Cost, $[c]
A	2700	675
B	5400	1350
C	5400	1350

[a] Model A has 1 accumulator vessel per unit, and Model Units B and C have 2 vessels each.

[b] Capital cost is based on 61 meters of 5.1 cm carbon steel pipe, $2700 installed per vent.

[c] Annualized cost based on a 10-year expected life and 10 percent interest; CRF = 0.16, Maintenance = 0.05, Miscellaneous = 0.04, Total = 0.25.

Table F-5. NATIONAL CAPITAL AND ANNUAL COSTS FOR CONTROLLING EXISTING ACCUMULATOR VESSELS

Model Unit		Capital Cost[a] ($1000)	Annualized Cost[b] ($1000)
A		19.6	4.9
B		19.5	4.9
C		6.5	1.7
	Total	45.6	11.5

[a] Assumes that 5 percent of existing accumulator vessels are uncontrolled and are tied into existing control devices.

Thus, the national capital costs for Model Unit A would be:

145 (number of existing units) x $2700 (control cost per unit) x 0.05 (5 percent uncontrolled) = $19,575.

[b] Annualized cost based on a 10-year expected life and 10 percent interest; CRF = 0.16, Maintenance = 0.05, Miscellaneous = 0.04, Total = 0.25.

Table F-6. NATIONWIDE COSTS FOR THE EXISTING INDUSTRY FOR REGULATORY ALTERNATIVES III, IV, AND V

Regulatory Alternative	Capital Cost ($ Million)			Annualized Cost ($ Million)		
	Accumulator Vessels	Other Sources*	New Total	Accumulator Vessels	Other Sources*	New Total
III	0.05	9.7	9.8	0.01	2.1	2.11
IV	0.05	25.3	25.4	0.01	5.5	5.51
V	0.05	242	242.1	0.01	58.6	58.61

*Other sources are ones for which control costs were estimated in Chapter 8 (Table 8-15).

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16. ABSTRACT

A national emission standard for petroleum refining and organic chemical manufacturing industries is being proposed under authority of Section 112 of the Clean Air Act (42 U.S.C. 7412, as amended). The purpose of the proposed standard is to minimize benzene fugitive emissions in these industries. The document provides background information for the proposed standard. Control technologies and five regulatory alternatives are evaluated in terms of environmental and economic impacts on both new and existing emission sources. Included in the evaluation of environmental impacts are estimates of air quality, water, noise, and solid waste impacts. Included in the evaluation of economic impacts are estimates of total capital and annualized costs, including recovery credits.

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a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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